TM 1-230

WAR DEPARTMENT

[U. S. Dept of Army]

TECHNICAL MANUAL

WEATHER MANUAL FOR PILOTS

TECHNICAL MANUAL No. 1-230

WAR DEPARTMENT,
WASHINGTON, *May 27, 1940.*

WEATHER MANUAL FOR PILOTS

Prepared under direction of the Chief of the Air Corps

SECTION I

GENERAL

1. **Purpose.**—The purpose of this manual is to provide the pilot with information concerning—

a. General system of collecting and distributing weather information.

b. Currently available weather services and the proper way to utilize them.

c. Weather maps, forecasts, and sequences, with their abbreviations, symbols, and nomenclatures.

d. Fundamentals of modern meteorology, including cyclonic structure and associated fronts.

e. Clouds.

f. Department of Agriculture Weather Bureau Circular "N," "Instructions for Airways Meteorological Service."

g. Weather conditions which make flying hazardous such as fog, ice formations, and thunderstorms.

h. Upper air data from free balloons, airplane weather observations, and the radio meteorograph.

i. Influence of terrain upon the weather.

j. How to make a decision regarding the weather.

2. **Etymology.**—Weather is strictly defined as the general condition of the atmosphere of a place at a given time, as regards its temperature, moisture, winds, clouds, and other elements. Meteorology is the science of the atmosphere. "Meteor" is derived from the Greek word "meteoros" which means, in air. Some of the types of meteors are luminous meteors—rainbows, auroras; igneous meteors—meteorites, shooting stars; and the more common and important water or hydrometeors such as rain, drizzle, hail, and snow. "Ology" is a suffix used in English words meaning science. Meteorology includes weather and climate. Climate is the sum total of the weather. The pilot is primarily interested in weather.

3. **History.**—*a.* Weather forecasting was probably practiced by animals even before the advent of man. References to weather phenomena exist in man's earliest writings. The first known systematic discussion of weather was the "Meteorologica" of Aristotle (384–322 B. C.). A pupil of Aristotle wrote on winds and weather signs. Then for 2,000 years there is no recorded advance in the knowledge of weather. The treatment of meteorology as an exact science began with the invention of the thermometer by Galileo in 1607 and was greatly aided by the invention of the barometer by Torricelli in 1653, the discovery of Boyle's law in 1659, and the introduction of the effect of the rotation of the earth on wind by Had-

ley in 1735. In 1747, Benjamin Franklin made the very important discovery that a storm is a moving formation.

b. The first weather charts were prepared by Lamarck, Laplace, and Lavoisier during the period from 1800 to 1815. These same men established the first network of observing stations. It was at this time that the movement of air-pressure systems was discovered. International cooperation began in 1853 and a British meteorological office was established in 1854.

c. The United States Weather Bureau began in 1870 as a part of the Signal Service under the direction of the War Department. The weather service continued under the direction of the Army until 1891, when the United States Weather Bureau was placed under the Department of Agriculture and has remained there ever since. The work of the United States Weather Bureau is divided into such subdivisions as agricultural, horticultural, insurance, marine, and aeronautical meteorology. The most recent is the aeronautical branch.

d. It was early learned that a rise of air pressure often meant good weather and that when the air pressure fell, bad weather might be expected. Forecasting procedure depended solely upon the treatment of surface data and the relation of moving air-pressure systems to weather changes; no serious attempt was made to offer an explanation of weather phenomena based upon sound physical principles. With the development of commercial and military aviation, a better method of attack became imperative.

4. Recent demands on weather forecaster.—*a.* In order to get a better understanding of why the recent advances in meteorology were necessary, it is desirable to enumerate the demands that are made upon the forecaster by the pilot of today. He is interested primarily in conditions in the atmosphere above the earth's surface. He must know—

(1) Levels where clouds will be encountered in flight.

(2) Regions where severe turbulence or bumpiness may be encountered.

(3) Wind distribution aloft in order that he may navigate his ship properly and take advantage of any tail winds that he may encounter.

(4) Levels where ice formation on the airplane may be expected.

(5) Conditions expected at the station where the flight terminates.

b. The conditions in (5) above become extremely important in modern flying where long distances are traveled over the tops of cloud systems or even within the clouds themselves. The pilot must know definitely before starting such a trip whether terminal conditions at the completion of the flight will be such that a landing can be made.

This usually boils down to a prediction of the ceiling and horizontal visibility expected at the terminal station at the time of arrival.

c. Weather forecasts for industrial or agricultural purposes may usually be stated in rather general terms; and if conditions vary somewhat from the prediction no harm is done. The aviation forecaster, however, cannot make many serious mistakes in his forecast without the possibility of tragic results.

d. The need for a study of weather from a three-dimensional instead of a two-dimensional point of view becomes apparent, and continued efforts in this direction will lead to a fuller understanding of the physical processes involved in weather changes. When this need became apparent, it gave new impetus in this country to the ideas which had been set forth during the past two decades by Norwegian meteorologists, notably V. and J. Bjerknes. They had proposed hypotheses explaining, from a physical point of view, the weather changes of the middle latitudes associated with the familiar migratory low pressure areas. These ideas, owing to their fundamental soundness, have given meteorologists in America a firm foundation upon which to develop a forecasting technique suitable for air operations. The use of the theories evolving from the work of the Norwegian meteorologists definitely yields the best solution to forecasting problems.

5. Importance of weather.—*a.* It has been said that to command a ship at sea with many lives aboard and not know one's location is to be in the very worst human situation. In a similar category is the commander of an aircraft without a knowledge of the neighboring meteorological conditions in the atmospheric ocean in which he is flying or leading other aircraft.

b. Numerous situations arise where meteorological knowledge means the saving of lives and equipment. Assuming that an expert forecaster is available before or during a flight, the commander himself must still possess the ability to understand fully the significance of the weather. Without this knowledge, correct decisions become a matter of chance. An error may involve unwarranted adverse conditions, head winds, ice formation on aircraft, unnecessary expenditure of fuel, or any one of many situations which will lead to disaster. A correct decision will obviate unnecessary losses and perhaps utilize existing conditions to further the ultimate success of the tactical mission.

6. Collection and dissemination of weather data.—*a.* Weather data are gathered from stations distributed throughout this country plus information gathered from other nations and ships at sea. Observations throughout the world are coordinated so that they are made simultaneously at a given Greenwich time.

b. The distribution of stations in the United States is most dense along the established air routes. Observations at airways stations are made hourly, and in addition those stations equipped with radio range broadcasting facilities make half-hourly observations. These reports are collected and distributed through existing communication systems. The larger radio range stations broadcast weather sequences hourly along specified routes. Most of these stations broadcast weather over several different routes, the weather sequences commencing at 43 minutes past the hour and continuing at 5-minute intervals for each of the several routes. Some of these sequences are followed by wind aloft reports. In addition, local weather is broadcast at 20 minutes past the hour. Terminal and airways forecasts are broadcast, usually near the half hour, by selected stations. Weather map data are received by all stations on the teletype circuits, these data also being broadcast by the United States Weather Bureau chiefly through the facilities of the naval radio stations at Arlington and Mare Island.

c. The weather stations at air terminals are operated by Weather Bureau personnel. At certain terminals, the Weather Bureau personnel prepare the airways forecasts which are used as the official forecasts in the operation of airlines in this country. Most of the large airlines maintain their own weather staffs which are used to supplement for their own particular needs the official data prepared by the United States Weather Bureau. The national teletype circuits are one of the distributing means of weather information and they are operated by the Civil Aeronautics Authority. Due to a shortage of personnel in the United States Weather Bureau, many observations at small airways stations are made by the Civil Aeronautics Authority personnel. The airways service of the United States Weather Bureau is rapidly expanding and improving both in the amount and quality of data distributed.

7. Air Corps Weather Service.—*a*. The United States Army Weather Service was conducted under the direction of the Signal Corps until 1937, when it was placed under the direction of the Air Corps. For the purpose of administering the Army Weather Service, the Air Corps has divided the United States into three regions which approximately coincide with the regions designated for the operation of each of the GHQ Air Force wings. The first weather region comprises roughly the Western States, the second weather region the Eastern States, and the third weather region the Middle States.

b. The organization of the Air Corps Weather Service consists of the Chief of the Weather Service in the office of the Chief of the Air

Corps, a GHQ Air Force weather officer, one weather squadron in each weather region, and stations at air fields located in foreign possessions. The weather squadron headquarters are located at March, Langley, and Barksdale Fields. The larger Air Corps fields are served by base weather stations which have an authorized complement of at least 2 officers and 15 enlisted men and operate on a 24-hour reporting and forecasting basis. Other Air Corps weather stations are designated as post, squadron, detachment, and airways observer stations. Their complement, duties, and hours of operation are determined by the needs of the stations.

c. The training of Air Corps weather personnel is conducted at each station, at the Air Corps Weather School for enlisted men at Patterson Field, Ohio, at the Massachusetts Institute of Technology, and at the California Institute of Technology. All Air Corps weather officers are required to be graduate meteorologists. The result of this procedure has been an amazingly rapid production of an efficient weather service for the United States Army and the Air Corps.

d. The personnel involved and the expensive equipment operated by the Air Corps demand that forecasts issued by the Air Corps Weather Service be as accurate as possible. In the light of modern developments in meteorology, there has been some question as to whether enlisted men can properly perform this service. Limitations as to the number of officers available have required the use of enlisted men as forecasters. Experience has shown that the training received at local weather stations together with that given at the Air Corps Weather School is sufficient to produce reliable enlisted forecasters.

e. Weather observations are made at Air Corps weather stations. These data, in most instances, are distributed on the national teletype circuits. The larger Air Corps stations broadcast local weather data usually on the hour and the half hour. Forecasts are broadcast at some Army stations. The times and frequencies of weather broadcasts made by the Army and other agencies are listed in the Air Corps radio facility charts, one of which should be carried by every pilot on a cross-country flight. The necessity for an Air Corps Weather Service in addition to that furnished by the United States Weather Bureau is demanded by the routine and tactical operation of Army aircraft. The detailed weather information required for the safe operation of Army aircraft is of such nature and volume that it is impossible for the United States Weather Bureau to completely fulfill this need. The Army uses United States Weather Bureau data when and where available.

f. Organization of the Air Corps Weather Service is outlined on the following chart:

OFFICE OF THE CHIEF OF THE AIR CORPS

- TRAINING
- GHQ AIR FORCE
- ALASKA
- PANAMA
  - France Field
  - Albrook Field
  - Howard Field
- HAWAII
  - Wheeler Field
  - Hickam Field
  - Luke Field
- PHILIPPINES
  - Nichols Field
  - Clark Field
- PUERTO RICO
  - Boringuen Field

FIRST WEATHER REGION

- MARCH FIELD
- HAMILTON FIELD
- McCORD FIELD
- MOFFET FIELD
- SACRAMENTO AIR DEPOT
- HILL FIELD

THIRD WEATHER REGION

- BARKSDALE FIELD
  - Fort Sill
  - Fort Crockett
  - Hatbox Field
  - Hensley Field
  - Fort Leavenworth
  - Fort Riley
  - Sloan Field
  - Biggs Field
  - Tucson
- KELLY FIELD
  - Duncan Field
  - Brooks Field
  - Fort McIntosh
  - Fort Clark
  - Dryden Field
  - Marfa
  - Matagorda
- MAXWELL FIELD
- RANDOLPH FIELD
- LOWRY FIELD
- MOBILE AIR DEPOT

SECOND WEATHER REGION

- LANGLEY FIELD
  - Fort Benning
  - Pope Field
  - Aberdeen Proving Ground
  - Middletown Air Depot
  - Pittsburg
- MITCHEL FIELD
- BOLLING FIELD
- SELFRIDGE FIELD
- PATTERSON FIELD
  - Wright Field
- SCOTT FIELD
- CHANUTE FIELD
- WESTOVER FIELD
- MACDILL FIELD

SECTION II

AIR MASS ANALYSIS

8. General.—The study of weather by methods originated in Norway has been termed "air mass analysis." A brief outline of the fundamental ideas involved forms the framework for the entire study of weather. Since these ideas will be expanded in later sections, it is very important that the student thoroughly understands the material given in the following paragraphs of this section.

9. Air masses.—It has been found that the earth's atmosphere consists of a number of extensive portions, each of which has individual characteristics. Within a given portion, these physical characteristics are approximately uniform in the various levels and each portion is called an "air mass." Therefore an air mass is a large portion of the earth's atmosphere that approximates horizontal homogeneity. The formation of an air mass is usually the result of the stagnation of a large portion of the earth's atmosphere over some rather uniform surface of either land or water for a period sufficiently long to enable its properties to reach equilibrium with respect to the surface beneath. At present, nine distinct air masses that frequent North America and adjacent oceans have been recognized. The Polar Pacific, Tropical Gulf, and Polar Continental air masses are among those that appear in the United States during the entire year. Some of the others have only a seasonal occurrence.

10. Source regions.—The region where an air mass acquires its initial physical characteristics is called its "source region." Source regions are usually confined to either high or low latitudes in combination with continental or maritime areas. These areas must be of rather uniform character both as to temperature and as to type of surface such as the North Pacific Ocean, North Central Canada, and the Gulf of Mexico. They must also be a region where air movements are rather sluggish in order to give the overlying air sufficient time to absorb its properties from the surface. Anticyclones or high pressure

areas are source regions because the air moves slowly within them and they often remain in one place for a considerable period of time. A cyclone is never a source region because it moves too fast, is formed by two or more different air masses, and travels over areas having different qualities.

11. Air mass movements.—*a*. Sooner or later the air masses take part in the general circulation of the atmosphere and migrate from their source regions. This movement carries the air masses across the middle latitudes where some modification of their initial properties takes place due to the changes in the temperature and type of surface over which they are passing. However, these new surfaces do not ordinarily cause abrupt changes within the air masses, therefore they may still be classified as entities having definite characteristics.

b. Warm air masses moving over colder ground exhibit different physical characteristics from cold air masses moving over warmer ground. Also warm air masses tend to overrun cold air masses and cold air masses tend to underrun warm air masses. Overrunning and underrunning are two great factors that influence the weather, especially in relatively flat areas. Therefore, it is essential that the pilot keep in mind—

(1) Whether the air in which he is flying is colder or warmer than the underlying surface of the earth.

(2) Whether there is overrunning or underrunning and which air masses are doing it.

12. Classification of air masses.—Air masses may be classified geographically as arctic, polar, tropical, and equatorial. Arctic air comes to the United States infrequently and equatorial air appears only at high altitudes. The general circulation of the atmosphere is such that only tropical and polar air masses frequent the middle latitudes. A thermodynamical classification calls for two types of air masses; warm and cold. A cold air mass is one that is colder than the surface over which it travels. A warm air mass is one that is warmer than the surface over which it travels. These definitions hold regardless of whether the air mass temperature is high or low. The relation between warm and cold air masses is purely relative. If two adjacent air masses have temperatures of 60° and 40°, respectively, the one with the temperature of 60° is a warm air mass in relation to the one with a temperature of 40°; whereas, if two other adjacent air masses have temperatures of 40° and 20°, the one with the temperature of 40° is a warm air mass in relation to the one with the temperature of 20°.

13. North American air masses.—*a*. A local classification for North American air masses has been developed. It is based upon the geographical location of the source region as well as whether the source region is in a polar or tropical area. The polar or tropical nature of the source region and the geographical location, together with the symbols used to denote the various types on a weather map, are enumerated below:

(1) Pc (Polar Continental) from the northern continental area.

(2) Pp (Polar Pacific) from the North Pacific Ocean.

(3) Pa (Polar Atlantic) from the North Atlantic Ocean.

(4) Pb (Polar Basin) from the Great Basin and Columbia Plateau.

(5) Ta (Tropical Atlantic) from the Sargasso Sea.

(6) Tg (Tropical Gulf) from the Gulf of Mexico and Caribbean Sea.

(7) Tc (Tropical Continental, usually originating from an old transitional polar type) from the southwestern continental area.

(8) Tp (Tropical Pacific) from the trade wind belt between California and the Hawaiian Islands.

(9) S (Superior) source region not definitely known, high level air probably from the Pacific area.

TABLE I

NORTH AMERICAN AIR MASSES Classification by local source regions				General classification after Bergeron (assume southward movement of polar types; northward movement of tropical types)
Nature of source	Local source regions	Air mass symbols	Season of frequent occurrence	
Continental	Alaska, Canada, and Arctic	Pc	Entire year	cP
	Modified over central and southern United States and over North Atlantic	wPc$_1$	Entire year	cPK or cPW over North Atlantic in summer
	Great Basin and Columbia Plateau	Pb	Fall, winter, and spring	cP
	Modified over central, eastern, and southwestern United States	Pb$_1$	Fall, winter, and spring	cPK

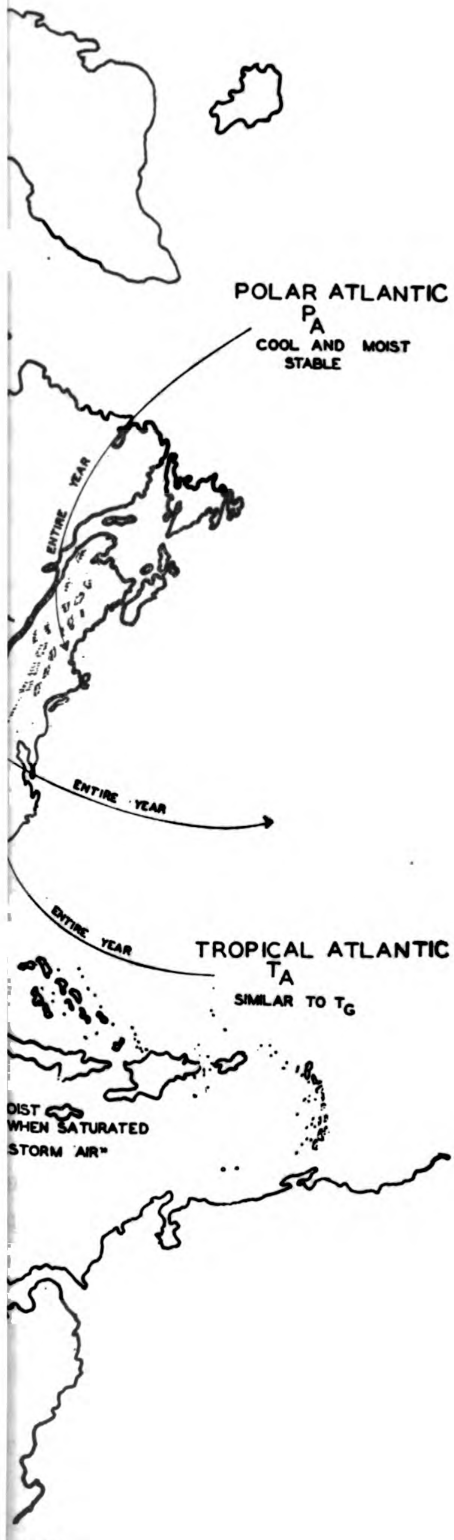
TABLE I—Continued

NORTH AMERICAN AIR MASSES Classification by local source regions				General classification after Bergeron (assume southward movement of polar types; northward movement of tropical types)
Nature of source	Local source regions	Air mass symbols	Season of frequent occurrence	
Maritime	North Pacific	Pp	Entire year	mP
	Modified over Pacific and United States	wPp$_1$	Entire year	mPK over ocean and cPW over land in winter; mPK or mPW over ocean and cPK over land in summer
	Colder portions of North Atlantic	Pa	Entire year	mP
	Modified over warmer portion of North Atlantic	wPa	Spring and summer	mPK
Continental	Southwestern United States and northern Mexico	Tc	Warmer half of year	cT
	Modified over central United States	Tc$_1$	Negligible	cTK
Maritime	Gulf of Mexico and Caribbean Sea	Tg	Entire year	mE
	Modified over United States or North Atlantic	wTg$_1$	Entire year	mEW in winter, mEK over land, mEW over water in summer
	Sargasso Sea	Ta	Entire year	mE
	Modified over United States or North Atlantic	wTa$_1$	Entire year	mEW in winter, mEK over land, mEW over water
	Trade wind belt between California and Hawaiian Islands	Tp	Winter and early spring	mT
	Modified over colder regions of North Pacific	wTp	Winter and early spring	mTW

b. As these masses leave their source regions and move rapidly across the middle latitudes where they interact to form the migratory cyclones and anticyclones of these regions, they undergo rather rapid modifications. The symbol "N" is now used, principally by meteorologists in eastern United States, to denote a transitional air mass. The change from the elementary symbol is an arbitrary one and various forecasters may have widely different ideas as to when the change should be made. To eliminate this difficulty and to give a more precise indication of the gradual modifications in the initial properties of any air mass resulting from its passage, either over a land or water surface (surfaces), which incidentally have very different thermal characteristics and therefore affect air masses crossing them quite differently, it is useful to indicate the period in the life history of a migrating air mass which has been spent both over a land surface and over a water surface. This is done by placing a subscript to the right of the symbol indicating the number of days it has traveled over a land surface since leaving its source and a subscript to the left of the symbol denoting the number of days it has passed over a water surface during its movement from the source. An example of this symbolization is as follows: ${}_3\mathrm{P}\textsc{p}_2$ indicates that at the position where this symbol is located on the weather map the air is of Polar Pacific origin and has traveled 3 days over water and 2 days over land since leaving the source region.

c. The classification of the American air masses as to their local source region and the season of their most frequent occurrence is given in table I. The air masses are classified according to their polar or tropical, continental or maritime origin, and the geographical location of the source. The air mass symbols at the source region are indicated and, in addition, those to be used after modification has taken place, the subscripts W and L having been added to the source region symbol to denote the history of the air in terms of its water or land trajectories respectively. The seasons of the year during which the various types occur most frequently are indicated and, finally in a general classification according to Bergeron, C and M represent continental and maritime while K and W mean cold and warm air masses.

14. Fronts (atmospheric discontinuity surfaces).—*a.* It is obvious that air masses originating in polar regions are materially different in structure from those attaining their initial characteristics over tropical latitudes. In the course of their migration over the earth's surface, dissimilar air mass types may be brought together. Instead of simply mixing, a rather definite boundary called a "front" or


POLAR ATLANTIC
P_A
COOL AND MOIST
STABLE
ENTIRE YEAR
ENTIRE YEAR
ENTIRE YEAR
TROPICAL ATLANTIC
T_A
SIMILAR TO T_G
WHEN SATURATED
STORM AIR"

lasses.

"surface of discontinuity" arises between them. This surface may be considered as a substantial surface, impenetrable by the air masses on either side as long as a marked discontinuity exists. This is easy to understand when it is realized that air is a fluid. Then these two dissimilar air masses are fluids of different densities, with the cold, dry polar air masses being heavier than the warm tropical masses. The cold, heavy masses will tend to underlie the warmer types.

b. As an illustration of the formation of a discontinuity surface between two dissimilar fluids, consider the case of oil and water confined in a vessel. If the fluids are allowed to reach the equilibrium state, it will be found that the water will underlie the oil which is the lighter of the two. A definite boundary surface will be visible between them which, if the fluids are not in motion, will take a horizontal position. This is entirely analagous to the case of a boundary surface separating polar and equatorial air currents. However, in the atmosphere, the fluids involved are ordinarily in motion, a condition which brings forces into action which cause the discontinuity surface to become sloping. It assumes a position such that the cold, heavy air underlies the warm, light air in the form of a very flat wedge. In fact, the slope of any atmospheric discontinuity surface is roughly of the order of 1 to 100. Since a weather map represents a plane surface, the sloping fronts or atmospheric discontinuity surfaces in the sea level plane represented by the weather map must intersect in a line. These atmospheric discontinuity surfaces form the boundaries of the air masses and when an air mass starts to move, its forward portion is bounded by a "front" named from that air mass. The frontal boundary of a migratory cold air mass is called a "cold front." The frontal boundary of a warm air mass is called a "warm front." Therefore, a warm front exists where warmer air is displacing colder air and a cold front exists where colder air is replacing warmer air, providing that the two air masses involved in each case are separated by a substantial discontinuity surface.

c. In general, cold fronts move southward and warm fronts move northward; however, there are exceptions. If a front is not moving, it is called a "stationary front." The name "occluded front" has been given to a front that has come in contact with another front in such a manner that the air originally at the surface between the two fronts has been forced aloft.

d. Warm-front slopes are of the order of 1/50 to 1/200 and cold-front slopes are of the order of 1/40 to 1/80. Since most stationary fronts act like warm fronts, their slopes have similar values.

15. Cyclones or atmospheric waves.—*a.* If it be assumed that an atmospheric discontinuity is formed between two dissimilar air masses, what will happen if its equilibrium be disturbed? We may

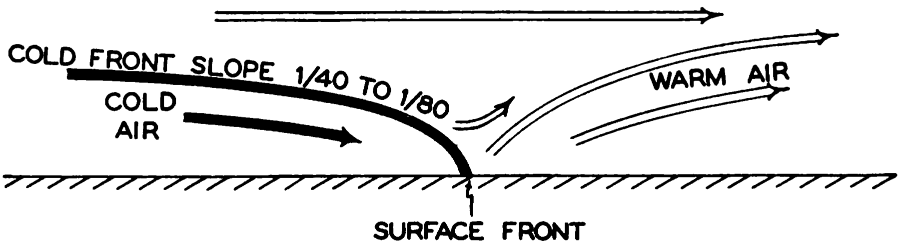


FIGURE 2.—Cold front (vertical section).

turn to a more familiar hydrodynamical analogy, the disturbance of a water surface, which may be considered as a discontinuity between a body of water and the air above it. Any disturbance of this discon-

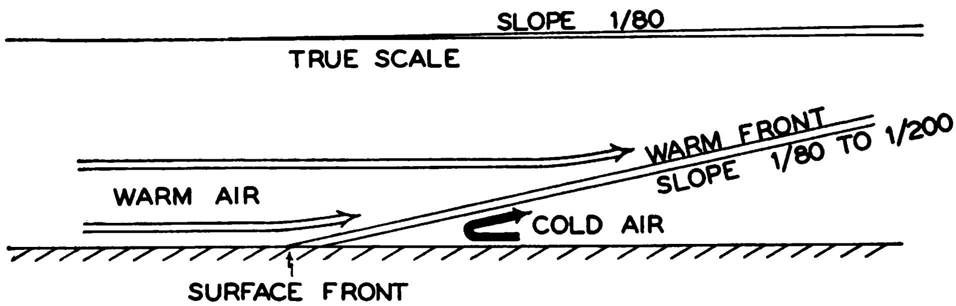


FIGURE 3.—Warm front (vertical section).

tinuity surface leads to the formation of waves along the discontinuity. For example, over the ocean a gentle breeze which actually represents relative motion between the two fluids, air and water, will produce

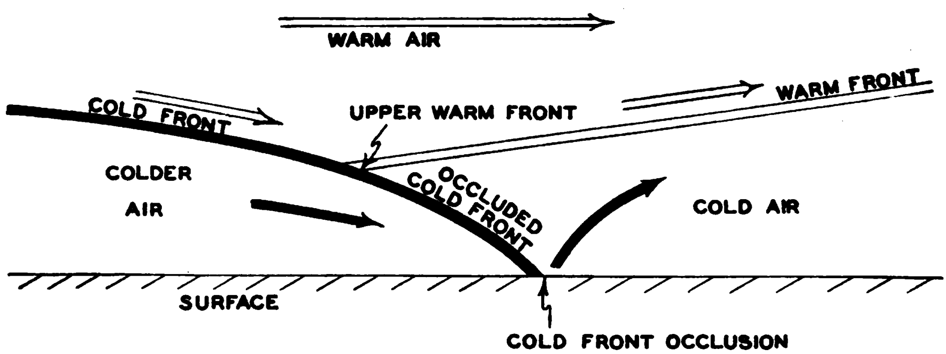


FIGURE 4.—Occluded front (cold-front occlusion).

waves and if the wind velocity exceeds a certain limit, the tops of the waves are removed in the form of whitecaps, which indicates that the discontinuity surface between air and water has become unstable and the two fluids are tending to whirl together.

b. In the atmosphere, a similar process takes place when the boundary between two dissimilar air masses is disturbed by an acceleration of either air mass adjacent to it. These waves are quite different from waves on the ocean, but they obey the same physical laws, and a forecaster with an understanding of wave theory is in a position to determine, at least qualitatively, the direction and rate of propagation of these systems. They are easily spotted on the weather map due to the fact that the discontinuity surface along which they form, being a sloping surface, must intersect the surface of the earth and therefore may be plotted upon a weather chart from surface observations.

c. When these atmospheric waves become unstable, a condition analogous to the formation of whitecaps on the ocean or breakers on the beach, the two air masses adjacent to the discontinuity surface tend to whirl together. This is called the "occlusion process."

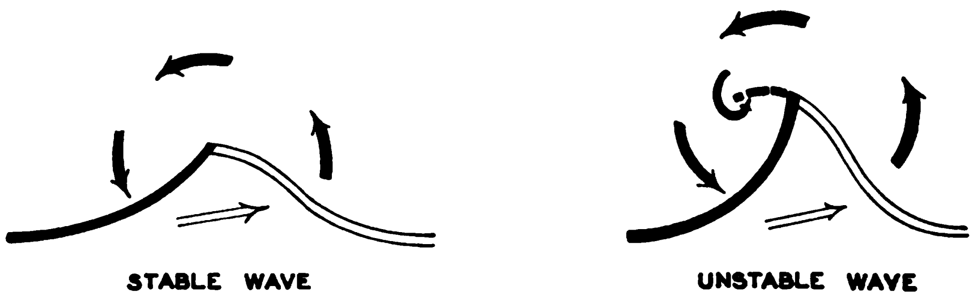


FIGURE 5.—Stable and unstable atmospheric waves (plan).

d. The crest of a wave forming along an atmospheric discontinuity occupies the center of a low-pressure area. This accounts for the well-known rule which associates bad weather with low-pressure areas. The major precipitation areas associated with a low are produced by a lifting of warm, moist air up over the wedge of cold air in its path, or as the warm air is pushed aloft, by the movement of the cold mass southward. This lifting of the air produces an expansion and consequent cooling which in turn may produce condensation forms and precipitation. The cloud types thus produced as well as the nature of the precipitation resulting are a function of the thermal structure of the air masses undergoing the vertical motion.

16. Life cycle of cyclones.—*a*. A very definite knowledge of the structure of all air masses encountered on the weather chart is essential to the pilot and forecaster. The interactions of the various air mass types occurring along their boundary surfaces become very important in forecasting cloud types, cloud levels, and all conditions in the free air. These interactions, as indicated above, are a function of the motions taking place not only between dissimilar types but

within the air masses themselves. All of these factors and their interrelationship must be determined as quickly and accurately as possible by the forecaster. The life history of a cyclone is shown in figure 6. Part A shows the front extending along in a line that is approximately straight. Detailed analyses of surface fronts have shown that they present many minor irregularities. Part B shows

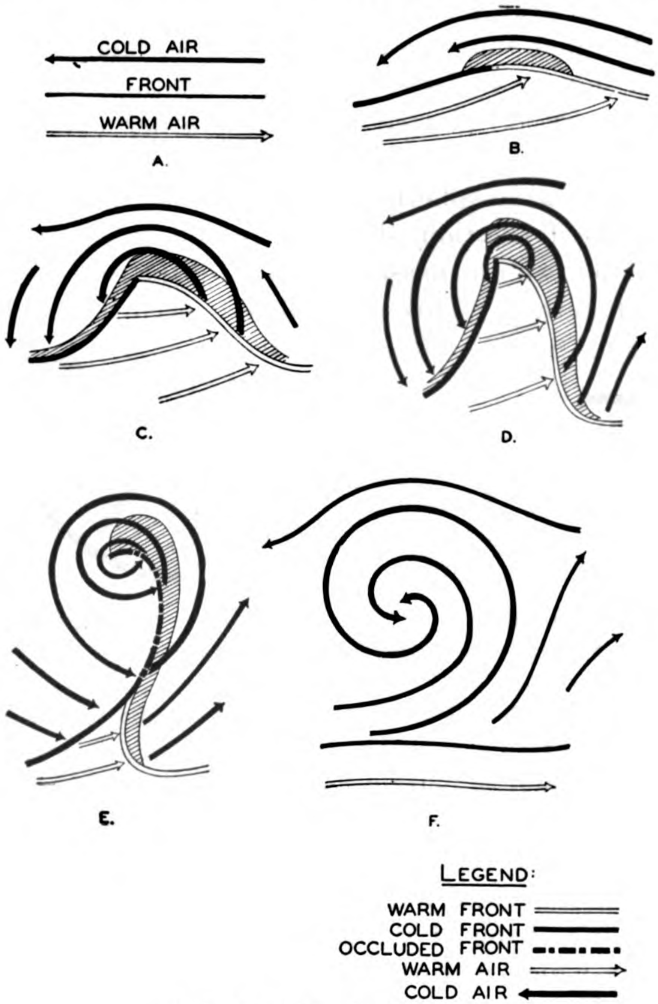


FIGURE 6.—Life cycle of a cyclone.

the development of one of these irregularities into a small wave with an associated precipitation area. It also shows that this precipitation area is due to the development of a component in the warm air perpendicular to the front. In part C, wave development has progressed to the point where there is a definite cyclonic circulation, a warm sector, a well-defined crest with warm and cold fronts on either side, and the typical precipitation areas. Due to the more rapid movement of the cold front, part D shows a narrowed warm sector and the

approach of the cold front to the warm front. In part E, the occlusion process is taking place, the cyclone has reached its maximum development, and the warm sector is being rapidly pinched off. In

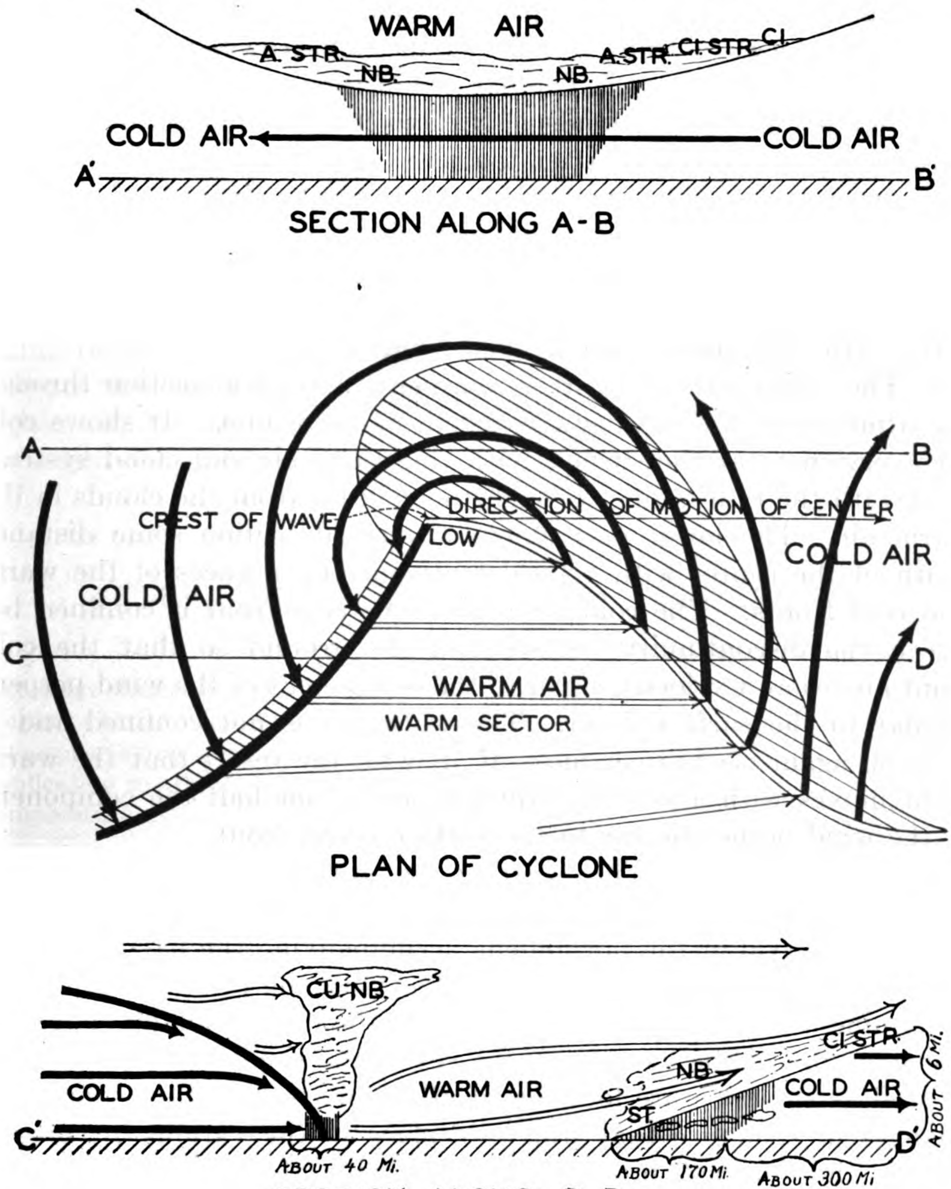


FIGURE 7.—Plan and vertical sections of a cyclone.

part F, the warm sector has been eliminated, the cyclone is in its dying stages and is represented only by a whirl of cold air that is rapidly dissipating in strength. Parts B, C, and D represent stable waves and part E represents an unstable wave; when waves begin to occlude they are said to be unstable. All fronts and waves shown

on the weather map may be interpreted as constituting some phase of the life cycle of a cyclone, as shown in figure 6.

b. Figure 7 shows a plan and two vertical sections of an ideal cyclone. The shaded portions show the precipitation areas, the largest of which is ahead of the warm front, but there is also a narrow band of precipitation along the cold front. The passage of the warm front is preceded by a large number of clouds of various types followed by quite a period of precipitation. After the passage of the warm front, there is an area where the sky is relatively clear and the air is warm. As the cold front approaches, clouds again begin to appear; there is a brief period of heavy precipitation during and shortly after the passage of the cold front and then the air is cold. Frequent showers occur for a time after the passage of the cold front.

c. The upper part of figure 7 represents a vertical section through the atmosphere a short distance north of the center. It shows cold air everywhere at the surface with the warm air and cloud systems aloft with the rain falling through the cold air from the clouds in the warm air. The lower part shows a vertical section some distance south of the center with typical sectional appearances of the warm and cold fronts. The cold air behind the cold front is confined between the discontinuity surface and the ground so that the cold front moves at a velocity equal to the component of the wind perpendicular to the surface front. The warm air is not confined and is pushing against a heavier mass of air with the result that the warm front moves with a velocity equal to about one-half the component of the wind perpendicular to the surface warm front.

17. Forecasts.—*a*. The weather at any particular location is determined by the characteristics of the air masses present during the forecast interval or the phenomena accompanying the passage of any air mass boundary during this period. Thus the meteorologist must determine as accurately as possible from the data available, not only the structure of the various air masses at the time the map is drawn as well as the accurate location of all air mass boundaries, but also changes in structure that will take place in the various air masses during the forecast interval together with the displacement and development of the frontal zones and their associated pressure systems during this period. All of these factors will affect the prediction of the weather over a particular route or at a particular station along the route. The determination of the above elements in preparing a forecast of a quantitative nature requires a liberal use of thermodynamical and hydrodynamical principles as applied to atmospheric movements and phenomena.

b. Many benefits may be derived from a continued study of the physical aspects of meteorology and its application to military aviation. Up to the present time, more consideration has been given to the short range forecasts covering the period occupied in making a flight between two stations than to long range forecasts covering weather conditions over an entire area for several days. This is due to the fact that the longer range forecasts are in general more difficult to make. However, they are particularly desirable in order better to coordinate planning the actual operations in several ways. Short range forecasts can minimize if not eliminate entirely so-called attempted flights and will materially decrease cancellations on account of weather. In case of a rather flexible system, they will enable flights to be routed correctly along alternate routes when conditions indicate such action. Finally, the more accurate the forecast, the higher will become the safety factor in operation and the lower the probability of serious mishaps.

SECTION III

ATMOSPHERE AND AIR MASS PROPERTIES

18. Molecular structure of the atmosphere.—*a*. Atmosphere is the gaseous layer which envelops the earth. The atmosphere is composed of ultramicroscopic particles called molecules that are rebounding against each other and are in ceaseless motion in all directions. The distribution of the number of molecules results from a compromise between the indefinite expansion toward space and their fall toward the earth, under the influence of gravity, which tends to accumulate them at the surface of the earth. Equilibrium is established in accordance with the following law: For each increase in altitude of 5½ kilometers above sea level, the number of molecules per unit volume decreases by about one-half. Thus the extreme altitude attainable by balloons is reached at about 150 kilometers. The phenomena which exist above this altitude must be studied by indirect means.

b. Since equilibrium in the atmosphere is a mean state, the number of molecules contained in a fixed volume varies with time. It is

because of this continual interchange that the atmosphere, even though it is clear, acts as a diffusing medium and, from the optical point of view, diffuses sunlight. Since the shorter wavelengths of light are blue and violet, they diffuse most readily and color the sky blue.

c. A few molecules possessing unusual speed escape the attraction of the earth when they arrive at the outer limits of the atmosphere. The atmosphere is being continually evaporated into interplanetary space, imperceptible in historical time, as the circumstances favorable to the escape of a single molecule are exceptional. It is this effect which must have almost totally deprived the moon of its atmosphere, because the gravity of the moon is about six times less than that of the earth.

19. Height of the atmosphere.—As the air continually becomes less dense with altitude, it is impossible to know the exact height of the atmosphere. However, there are certain phenomena which prove the existence of air molecules at considerable heights. In the twelfth century, Arabic astronomers appreciated the thickness of the atmosphere because of the duration of twilight. After the sun sets, light is still reflected toward the earth by the higher layers of the atmosphere. Calculation has shown that the highest layers capable of diffusing sunlight occur at about 60 kilometers. Luminous or pearl clouds, whose altitudes have been definitely established by triangulation, have been observed at night at altitudes of 80 kilometers. Shooting stars appear at about 300 kilometers. Even at this altitude, the air is dense enough for the heat caused by the friction of a rapidly moving solid body to emit light. The Aurora Borealis have a maximum frequency at about 100 kilometers, while some rays reach to altitudes of 1,000 kilometers. The study of the propagation of radio waves has led to the conclusion that an ionized zone called the Heaviside Layer exists at an elevation of more than 80 kilometers.

20. Atmospheric pressure.—Any surface that is introduced into the atmosphere is subjected to an incessant bombardment by air molecules, the effect of which is called "atmospheric pressure." It can be shown that this pressure is equal to the weight of the column of air which lies above the surface. Torricelli's experiment illustrates this effect and has made its measurement possible.

a. Torricelli's experiment (*mercurial barometer*).—(1) If a glass tube 1 meter in length is filled with mercury and inverted over an open vessel containing mercury, the liquid column descends and leaves a vacuum above the mercury. The top of the descending column stops at a vertical distance Z (fig. 8) from the surface of the mercury in

the vessel. The distance Z is independent of the form or inclination of the tube and at sea level will be about 29.92 inches (1,013 millibars). The two points A and B located at the surface of the mercury, point A outside, point B inside the tube, support the same pressure. Point B supports the weight of the column of mercury Z. It is obvious that the height Z, of the mercury, measures the atmospheric pressure.

(2) The mercurial barometer employs the principle of the experiment just described. The barometers used in meteorology are constructed to allow very accurate determinations of the length Z of the

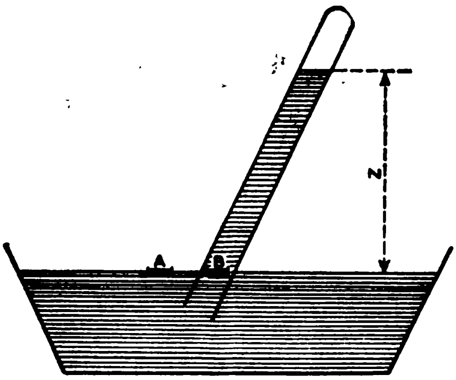


FIGURE 8.—Principle of the mercurial barometer.

mercury column. It is possible to obtain readings to 0.01 of an inch and even to 0.001 of an inch with the aid of a vernier.

(3) The readings of a mercurial barometer are absolute. Aneroid barometers are set by reference to mercurial barometers.

b. Units of atmospheric pressure.—(1) Atmospheric pressure can be measured by the height of the column of mercury expressed in inches and hundredths of inches. Thus, the mean atmospheric pressure at sea level is about 29.92 inches (1,013 millibars) of mercury. This means that a surface 1 inch square supports a force equal to the weight of a column of mercury 29.92 inches long and 1 inch square.

(2) Mercury weighs 13.6 times as much as water and a cubic foot of water weighs 62.5 pounds; a cubic foot of mercury weighs $13.6 \times 62.5 = 850$ pounds; 29.92 cubic inches of mercury weigh $29.92/1728 \times 850 = 14.7$ pounds. Therefore, the atmospheric pressure at sea level is about 14.7 lb./in.^{2}

(3) For several years meteorologists have, in order to facilitate their calculations, substituted for inches of mercury a unit that is more representative called the "millibar." A bar is a force of one dyne/cm.^{2} One millibar equals about 0.03 inch. Normal atmospheric pressure at sea level has a value of about 1,013 millibars. Pressures plotted

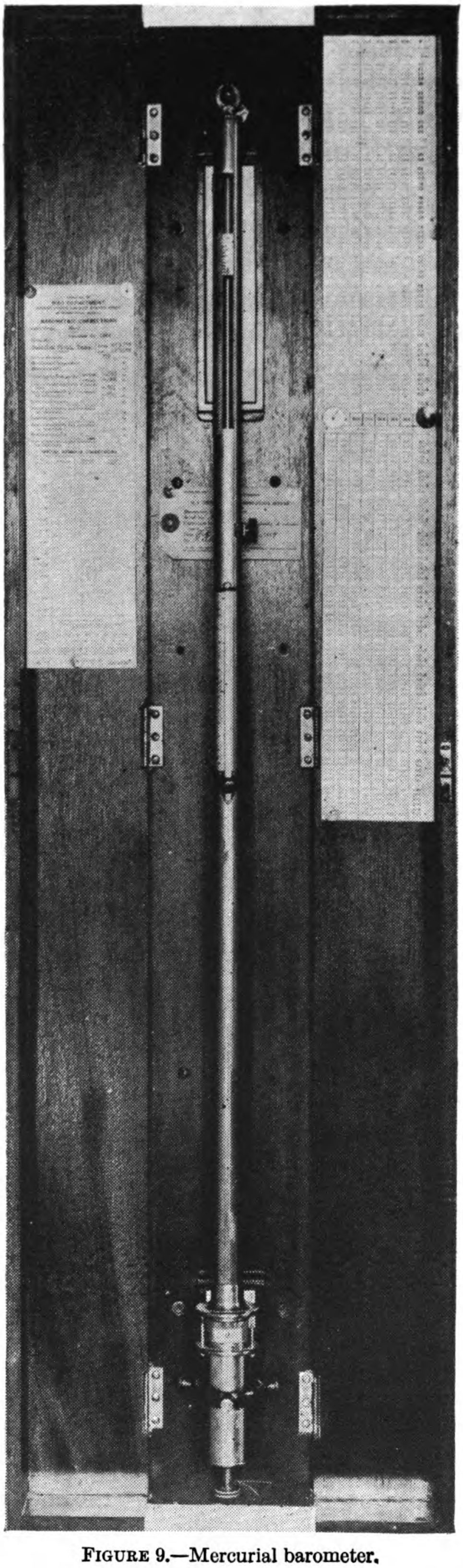


FIGURE 9.—Mercurial barometer.

on the weather map have been reduced to sea level and are given in millibars and tenths of a millibar.

c. Metallic or aneroid barometers.—(1) Mercurial barometers are cumbersome, fragile, and difficult to transport. Where great precision is not required, aneroid barometers are used. In these barometers, the actuating element is an evacuated metallic cell. No force is exerted upon the inner surfaces while the outer ones are continually subjected to a molecular bombardment which would crush the cell

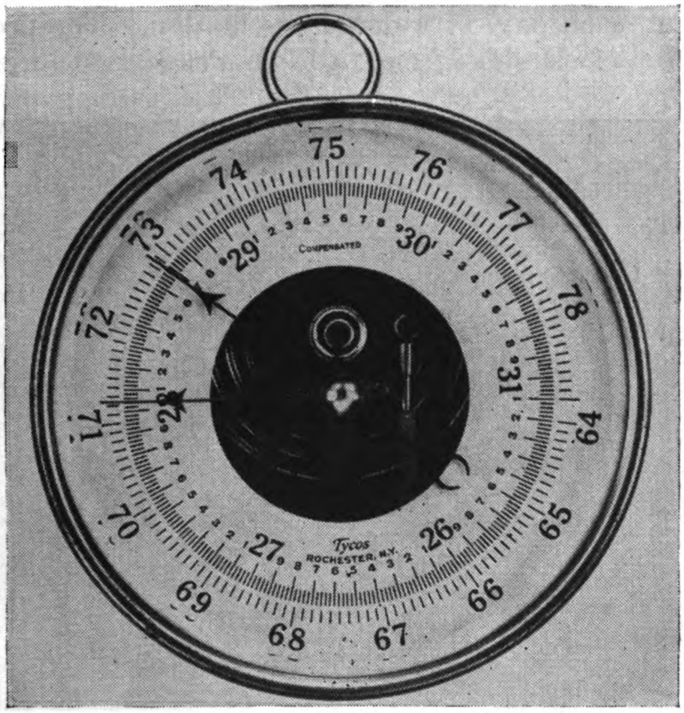


FIGURE 10.—Aneroid barometer.

if it were not held in shape by a strong spring that exerts a force of about 14.7 lbs./in.[2] Atmospheric pressure and its variations can then be measured by the deformation of the cell. This movement is transmitted by a system of levers to a needle that moves over a graduated scale.

(2) It is essential that the cell be evacuated. Otherwise, it would function, in part, as a thermometer due to the expansion and contraction of the interior air with variations of temperature. Aneroid barometers do not indicate the absolute value of the air pressure and they are easily deranged. Consequently, they must be compared frequently to a mercurial barometer.

d. Barographs.—A barograph is a recording aneroid barometer in which the pressure variations are transmitted by a system of levers to

a pen arm which makes a trace on a record sheet that surrounds a cylinder revolving at constant speed. Most record sheets have space for 1 week's trace. When more accuracy is desired, there is substituted for the paper record sheet, a metallic sheet blackened by smoke. Transport airplanes frequently carry an instrument called a flight recorder, one element of which is a barograph.

e. Variation of atmospheric pressure at a given place.—There are two kinds of variations of barometric pressure at a given place:

(1) A regular variation, known as the "diurnal variation," which has the form, each day, of a double oscillation. The pressure rises from 4 to 10 o'clock, sinks from 10 to 16 o'clock, rises from 16 to 22

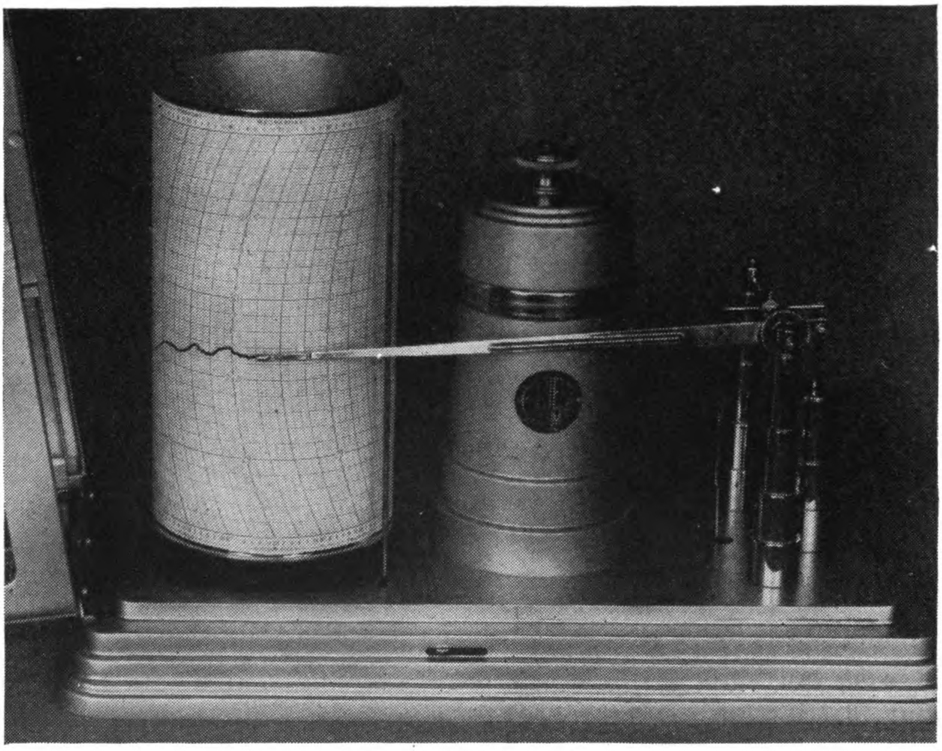


FIGURE 11.—Barograph.

o'clock, sinks from 22 to 4 o'clock (local time). The amplitude of the oscillation decreases with an increase in the latitude and the altitude of a station and is less in winter than in summer; it varies also with the time of day. It varies from 0.04 inch (1.35 millibars) in the middle latitudes to more than 0.15 inch (5.08 millibars) in tropical regions.

(2) The irregular or "dynamic variation" of about 0.50 inch (16.95 millibars) is due to the movements of pressure systems over the surface of the earth and local causes such as thunderstorms. The change of barometric pressure during a 3-hour period is called the barometric

"tendency." Tendency is plotted on the weather map and is one of the most important elements given because it is the only plotted element that shows the changes that have occurred over a given period of time.

f. Decrease of pressure with altitude.—The decrease with altitude of the number of molecules per unit volume results in a decrease of pressure with altitude. Remembering that the barometric pressure at a given place is equal to the weight of the column of air above, it is seen that as altitude increases, the pressure is diminished by the weight of the mass left below. If air were an incompressible fluid, like water, the decrease of pressure with altitude would be inversely proportional to the change in altitude, but since air is compressible, the lower layers are, for the same thickness, heavier than the higher layers. Consequently the pressure decreases less and less slowly with altitude. The cold, heavy air masses have a more rapid rate of decrease of pressure with altitude than the warm air masses.

21. Application to altimeters.—Since each atmospheric pressure value corresponds to a mean altitude, a barometer may be used to measure altitude. Altitude graduations corresponding to the pressure values given in the tables below are used. This is how an aneroid barometer is converted into an altimeter.

a. Setting the altimeter.—(1) The sea-level pressure varies because of the two factors given in paragraph 20*e*. Altimeters are calibrated to a sea-level pressure of 29.92 inches (1,013 millibars) of mercury (Hg). When the sea-level pressure varies from this value, the altimeter does not indicate the true elevation and must be reset by the pilot. A change in pressure of 0.01 inch (.339 millibar) (Hg) causes a change of roughly 9.5 feet on the altimeter for the first few thousand feet. Since the flight altitudes prescribed by Federal regulations are altitudes above sea level, the altimeter should be set for cross-country flying in accordance with the existing sea-level pressure. This means that before take-off and while in flight, the pilot should check frequently and reset the altimeter for existing sea-level pressure or he will not know accurately his elevation above the ground or any obstacles in his path.

(2) For example, assume a flight from Newark to Chicago on January 4, 1939, with take-off at 8 p. m. or 2000 eastern standard time (E. S. T.). The sea-level pressure at Newark was 30.48 inches (1,033.3 millibars) of Hg. It would have been necessary to increase the indicated elevation by 514 feet before take-off since the altimeter would have read 514 feet too low because of the above normal barometric pressure. Assuming a 3-hour flight to Chicago, the pilot would

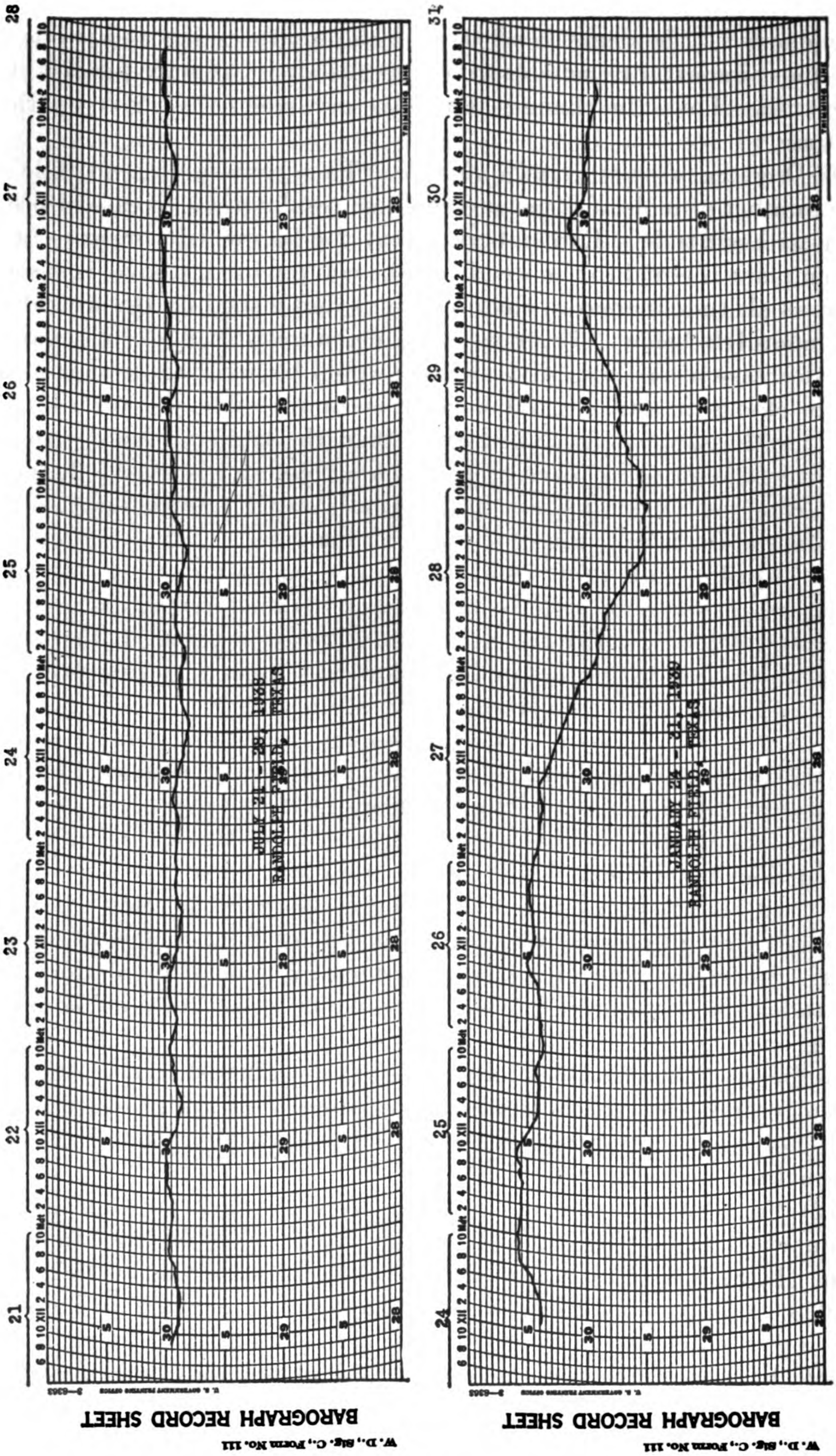


FIGURE 12.—Barograph record sheets showing diurnal and dynamic pressure variations.

have reached Chicago at 10 p. m. or 2200 central standard time (C. S. T.). At that hour, the class of flying required in that control zone was "instrument" or class "N" because the ceiling was 600 feet and the visibility was 4 miles with a light fog. The ceiling and visibility had recently increased from 300 feet and ½ mile. The sea-level pressure was 29.55 inches (1,000.1 millibars) of Hg which would have made the reading of the altimeter, at all elevations, too high by 858 feet. It is apparent that there would have been the possibility of disastrous results all along the route and particularly over the Appalachian Mountains and near cities with their obstacles, if the pilot

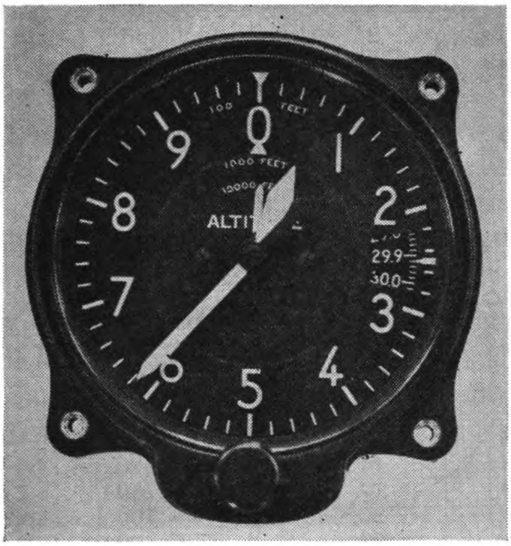


FIGURE 13.—Altimeter set at sea-level pressure of 29.92 inches (1,013 millibars) (Hg).

had not frequently reset his altimeter to agree with the sea-level pressures of the stations along the route.

b. Pressure-altitude tables.—The tables below show various relations between pressure and altitude. They are constructed on the basis of the International Standard Atmosphere which assumes a sea-level pressure of 29.921 inches (1,013 millibars) of Hg, temperature 59° F., and a temperature change with altitude of 3.57° F./1,000 feet. Altimeters are constructed on the basis of this atmosphere. It rarely, if ever, exists in nature but is a close approximation to average conditions. True altitudes may be determined from the altimeter by correcting for the existing sea-level pressure and the mean temperature of the air column.

TABLE II

Feet	Inches
18, 000	14. 94
17, 000	15. 56
16, 000	16. 21
15, 000	16. 88
14, 000	17. 57
13, 000	18. 29
12, 000	19. 03
11, 000	19. 79
10, 000	20. 58
9, 000	21. 38
8, 000	22. 22
7, 000	23. 09
6, 000	23. 98
5, 000	24. 89
4, 000	25. 84
3, 000	26. 81
2, 000	27. 82
1, 000	28. 86
Sea level	29. 921

Standard pressures at 1,000-foot levels.

TABLE III

Feet	Inches
19, 696	13. 92
18, 026	14. 92
16, 445	15. 92
14, 942	16. 92
13, 509	17. 92
12, 140	18. 92
10, 829	19. 92
9, 571	20. 92
8, 358	21. 92
7, 190	22. 92
6, 063	23. 92
4, 973	24. 92
3, 918	25. 92
2, 896	26. 92
1, 903	27. 92
939	28. 92
Sea level	29. 92

Elevations at 1-inch pressure changes.

TABLE IV

Millibars	Inches Hg	Feet	Meters
400	11. 80	24, 370	7, 425
500	14. 75	18, 520	5, 643
600	17. 70	13, 740	4, 186
700	20. 65	9, 700	2, 955
800	23. 63	6, 200	1, 889
900	26. 58	3, 112	948
1, 000	29. 53	348	106
1, 013	29. 92	Sea	Level

Vertical relation of 100 millibar levels.

22. Temperature.—Temperature is the degree of heat. It is usually measured according to the Fahrenheit, Centigrade, or Absolute scales, the relations between which are shown in table V.

TABLE V.—*Conversion table*

Absolute	Centigrade	Fahrenheit	Absolute	Centigrade	Fahrenheit
373	100	212.0	303	30	86.0
368	95	203.0	298	25	77.0
363	90	194.0	293	20	68.0
358	85	185.0	288	15	59.0
353	80	176.0	283	10	50.0
348	75	167.0	278	5	41.0
343	70	158.0	273	±0	32.0
338	65	149.0	268	−5	23.0
333	60	140.0	263	−10	14.0
328	55	131.0	253	−20	−4.0
323	50	122.0	223	−50	−58.0
318	45	113.0	173	−100	−148.0
313	40	104.0	0	−273	−459.0
308	35	95.0			

a. Radiation and heat absorption by the atmosphere.—(1) The sun may be considered as the sole source of heat energy supplied to the atmosphere and the surface of the earth. This energy is transmitted through interplanetary space by "radiation." The two other methods of heat transfer are "conduction" and "convection."

(2) If an observer sits before a bonfire, his face gets hot and his back gets cold. When a screen is placed between the observer and the fire, the heat is cut off. This shows that heat is propagated by rays which are analogous to light rays. The rays emitted by an electric radiator with a paraboloid reflecting surface travel in parallel bands. Anyone in the path of these rays feels a strong sensation of heat which disappears if the radiator is moved. The propagation of heat by rays is called "radiation." Radiation does not require the aid of a material medium for the transfer of heat. It is by solar radiation or insolation that heat is transmitted through interplanetary space to the atmosphere and earth.

(3) Assuming an average cloudiness of 52 percent, and considering average conditions over the entire earth of the total amount of solar radiation received at the outer limits of the atmosphere, 43 percent is reflected back to space, 17 percent is absorbed by the atmosphere, 40 percent is absorbed by the earth. Since the average temperature of the surface of the earth is almost constant, the earth is reradiating the same amount of heat in the form of terrestrial radiation that it receives as solar radiation. Almost all of this terrestrial radiation is absorbed and changed into heat by the atmosphere. Hence, the air receives more than twice as much heat directly from the surface of the earth as it does directly from the sun. This accounts for the fact that after the sun comes up, the bases and tops of clouds usually go

up rather than come down. If they were getting most of their heat from above, they would dissipate from the top down. Normally, the base goes up faster than the top to cause dissipation later in the day of clouds that are formed early in the morning.

(4) The explanation of the above phenomena is based upon the relative ability of the atmosphere to absorb solar and terrestrial radiation. Radiant energy is transmitted in the form of waves whose lengths are inversely proportional to the temperature of the radiating body. Assuming the sun to radiate at a temperature of 6,000° A.,

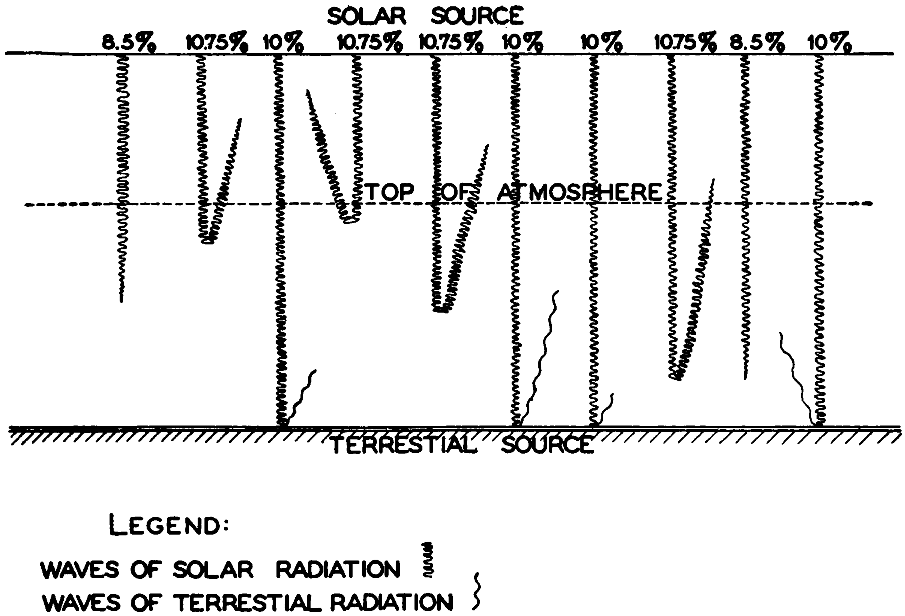


FIGURE 14.—Relative absorption of solar and terrestrial radiation by the atmosphere.

the maximum amount of radiant energy is transmitted at wave lengths of about 0.47 microns (1 micron = 1/1000 mm). The air does not have the ability to readily absorb energy from such short wave lengths. The earth radiates at a temperature of about 287° A., with maximum energy being emitted at a wave length of 10 microns. The atmosphere readily absorbs energy from these waves which are about 20 times as long as those from the sun.

(5) Water vapor is by far the most important heat-absorbing agent in the atmosphere. Carbon dioxide and the other elements absorb heat in small quantities compared to water vapor. Air that contains a large amount of water vapor will become heated by radiation much more readily than dry air.

(6) In equatorial regions, there is more solar radiation and consequently more terrestrial radiation per unit area than in polar areas. The result is more evaporation and more moisture in the air near the

Equator than near the poles. Since water vapor is the chief heat-absorbing agent in the atmosphere, more heat is absorbed by tropical air masses than is reflected back into space. In the middle latitudes, the amount of heat absorbed is about equal to the amount of heat reflected. As the pole is approached, polar air masses absorb less heat than is reflected back into space. The total result is that there is an unequal heat distribution in the atmosphere and since the general tendency of any fluid is to flow from the cold source to the warm source in the lower levels, this explains the fact that the winds of the earth tend to move from north to south. This would be a regular, uninterrupted motion if the surface were uniform in character and if the earth did not rotate. These two factors combined with the unequal heat distribution in the atmosphere are responsible for the variations in wind direction.

b. Conduction.—"Conduction" is the transfer of heat through matter by molecular contact.

(1) A person cannot touch an aluminum vessel filled with boiling water without becoming burned. This is because the heat of the water is transmitted through the metal. Therefore, aluminum is called a good conductor of heat. A wooden handle attached to this vessel could be touched safely because wood is a poor conductor of heat. Air is a poor conductor.

(2) The air molecules that come in contact with the ground are usually heated by conduction during the day and cooled by the same process during the night. This explains in part the rapid rate of decrease of temperature in the air above a hot plate, hot pavement, and, in a less sensitive degree, over the ground. This state of the air near the ground causes convection.

c. Convection.—(1) The transport of heat by matter in motion is called "convection." Air in motion transfers heat readily, simply by the movement of the warm or cold air from one place to another. The air in contact with a hot stove is heated, rises, and makes room for the surrounding cold air which is heated in its turn. The stove heats the entire room because successive masses of air are made lighter and put in motion by contact with the hot stove.

(2) Convection may be vertical, horizontal, or at any angle in between. However, since the earth supplies the major portion of the heat of the air, the vertical motions in the atmosphere caused by the higher temperature of the air near the ground are usually referred to as convections.

d. Thermometers.—The temperatures that are considered in meteorology are those of the free air. In order to measure them correctly,

it is necessary to have a thermometer which is in equilibrium with the temperature of the free air, and it should change only with a change of air temperature. Therefore, it is necessary to protect thermometers from radiation from the sun, the ground, the observer, and surrounding objects. In an airplane, the thermometer must be protected from the influences of the engine, other parts of the airplane, and the sun. Thermometers used at weather stations are

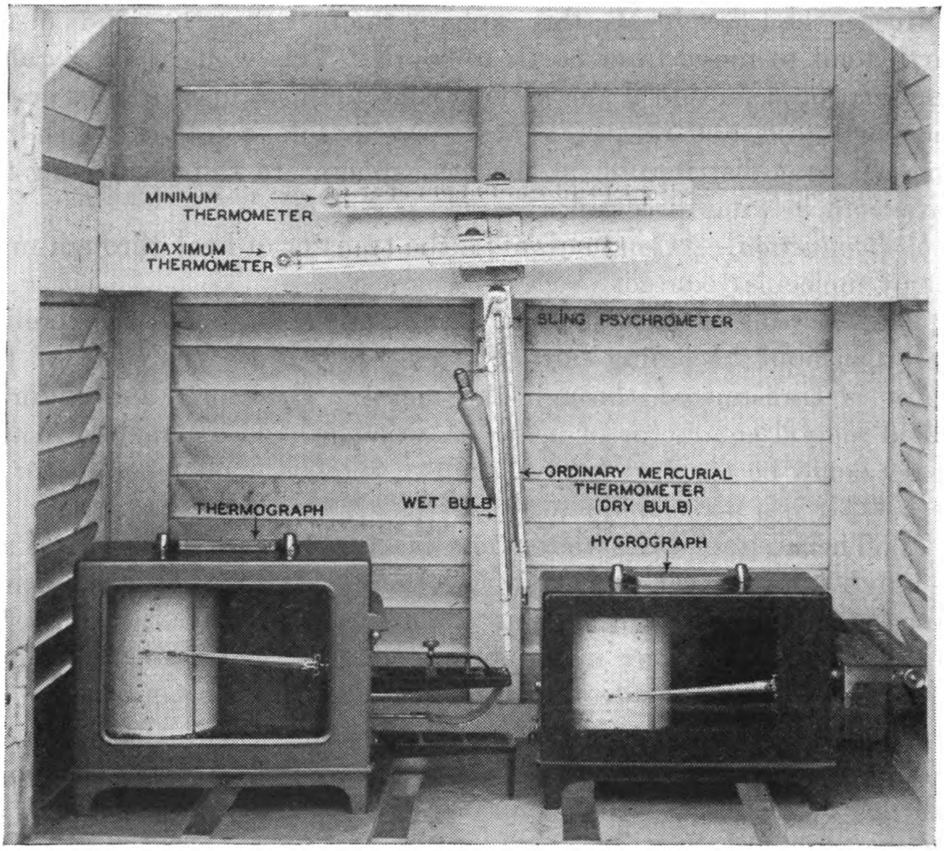


FIGURE 15.—Shelter with instruments.

protected by an instrument shelter. The different thermometers that are employed are as follows:

(1) *Ordinary mercurial thermometer.*

(2) *Sling thermometer,* a thermometer mounted so that it may be whirled and thereby rapidly attain the temperature of the free air. This type of thermometer does not need to be protected between observations.

(3) *Maximum thermometer,* a mercurial thermometer with a constriction near the base of the scale similar to a medical thermometer. When the temperature rises, the mercury expands and is forced past

the constriction, but when the temperature falls, the mercury column breaks at the constriction leaving the temperature indication at its maximum value. (See fig. 15.)

(4) *Minimum thermometer*, an alcohol thermometer with an index that allows the alcohol to flow by it as the temperature rises but which is carried down by the meniscus at the top of the alcohol. When the temperature goes down, the alcohol shrinks. (See fig. 15.)

(5) *Thermograph*, a recording instrument that gives a continuous record of the temperature. It is actuated by a Bourdon tube filled with alcohol connected to a pen arm in contact with a rotating cylinder. As the temperature changes, the alcohol expands or contracts, thereby causing the Bourdon tube to be displaced at its free end which is

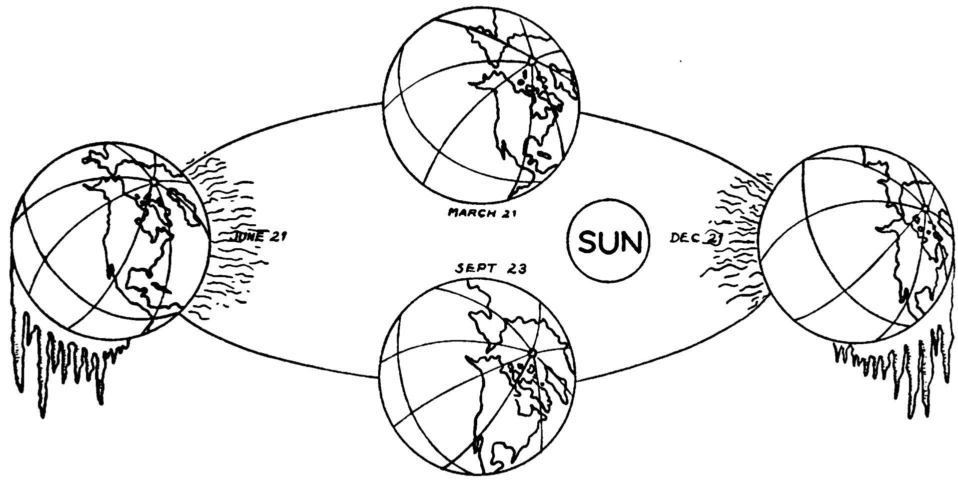
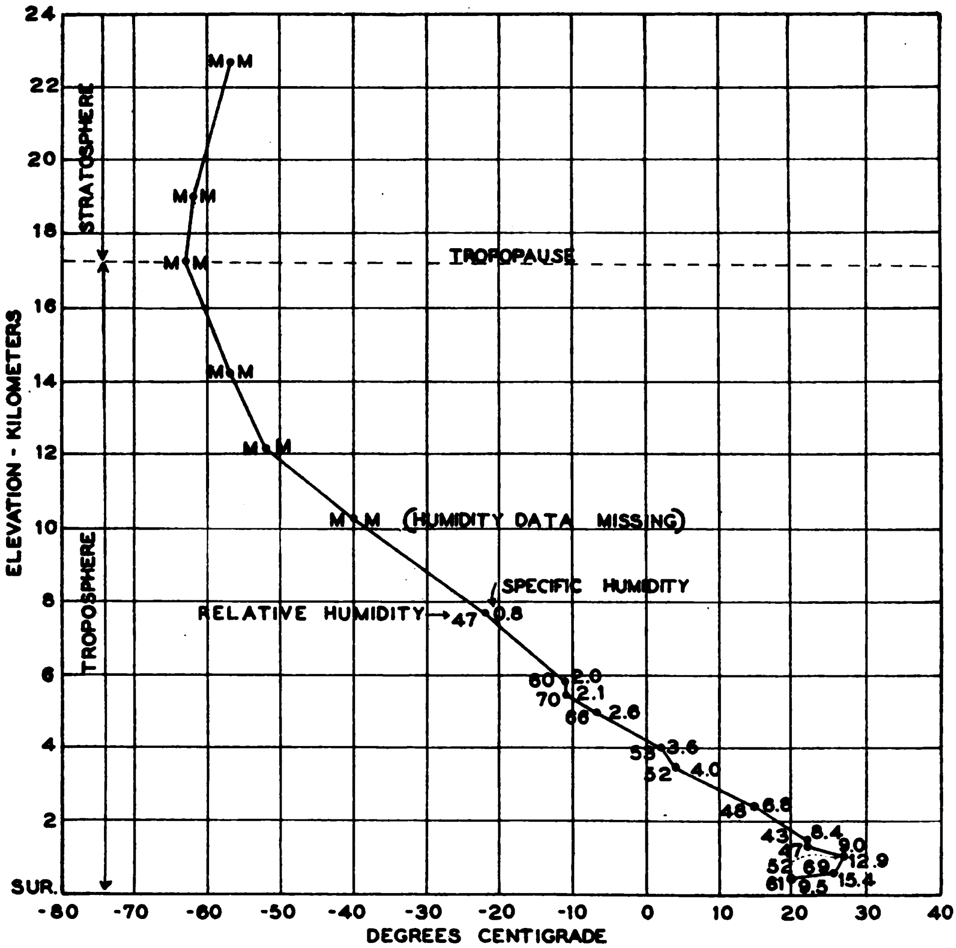


FIGURE 16.—The earth and its orbit in relation to the sun.

connected to the pen arm. Sometimes the Bourdon tube is replaced by a bimetallic bar which is actuated by the unequal expansion or contraction of the two metals when the temperature changes. (See fig. 15.)

e. Variation of temperature at a fixed station.—Similar to pressure, temperature undergoes, at a given place, regular and irregular variations. The irregular variations are caused by the changes in weather and are used in forecasting. The regular variation, called the "diurnal variation," occurs daily. It is caused by the variation in the height of the sun during the course of the day. Temperature is at a minimum near sunrise and at a maximum 2 to 4 hours after noon. Temperature also exhibits an annual variation caused by the relative position of the earth and the sun during the course of a year. Figure 16 shows the cause of the annual variation and its relation to the seasons. The seasons are due to the fact that the earth's axis is tilted at an angle of

23½° from the perpendicular to the plane of revolution and not due to the varying distance of the sun from the earth. The earth is closest to the sun during winter in the Northern Hemisphere. Figure 16 shows why the seasons are reversed in the Southern Hemisphere. Astronomically, winter should be more severe in the Southern Hemis-



STATION: OKLAHOMA CITY AIR MASS: RP_p TO ABOVE 6 KM.
DATE: SEPTEMBER 26,1938 TIME: 0400 CS

FIGURE 17. Variation of temperature with altitude.

sphere, but it is not, due to the unequal land and water distribution in the two hemispheres.

f. Variation of temperature with altitude (lapse rate).—(1) The change of temperature with altitude is of fundamental importance in determining the processes of weather. Ordinarily, there is an irregular variation in the first few thousand feet above which the temperature decreases with height at the rate of approximately 6° C./km. This is

about 2° C./1,000 feet or about 3½° F./1,000 feet. The rate of change of temperature with altitude is defined as the "lapse rate." At about 35,000 feet in the middle latitudes, a point is reached at which the temperature decrease with height ceases and above which the temperature remains constant or even increases. This variation of temperature with altitude is so constant and so remarkable that meteorologists have given special names to the two regions concerned.

(2) The layer where the temperature decreases regularly at the rate of 6° C./km. is called the "troposphere." It contains about three-fourths of the atmosphere by weight and almost all the water

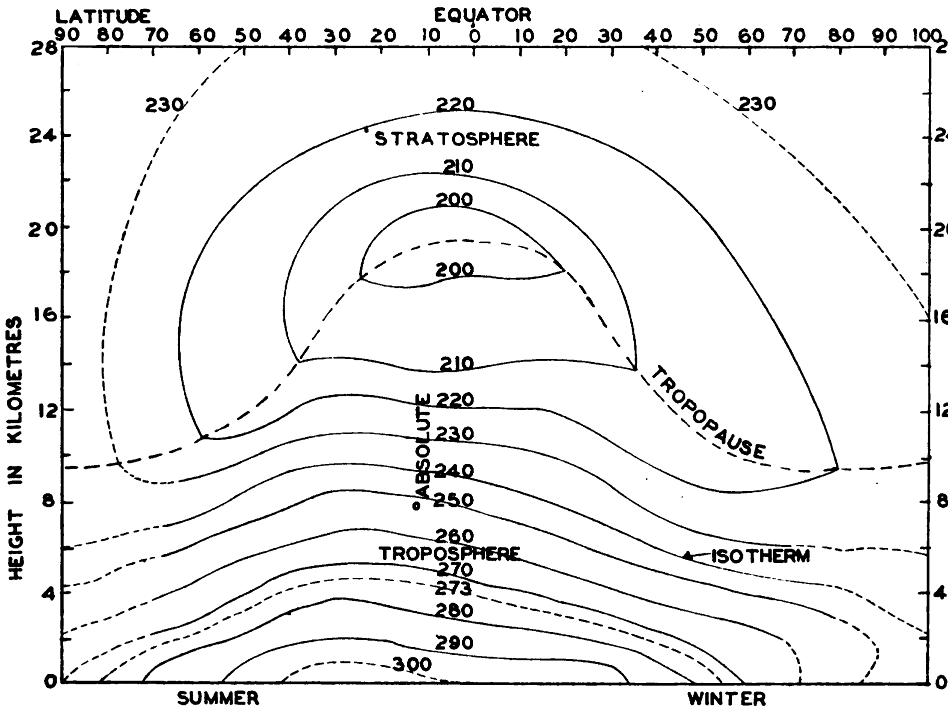


FIGURE 18.—Temperature distribution along a meridianal section of the atmosphere.

vapor. It is the region of almost all the hydrometeors such as clouds, rain, snow, and ice, and is at present the chief region of aeronautical activity. The layer where the temperature remains constant or increases with altitude, the stratosphere, is a clear and dry zone. Pearl clouds observed at 25 to 30 kilometers occur rarely, and may be due to meteoric or volcanic dust. The high stratosphere contains the major portion of the ozone in the atmosphere; however, the composition of the air there is the same as it is near the ground. It is not known exactly how far the stratosphere extends, but it is probable that it reaches to about 50 kilometers above which the temperature probably increases to rather high values. Experiments with sound

have shown that the noise from a loud explosion is most intense in the area near the source, decreases outward and then increases again to a fairly high intensity at a distance of about 125 miles beyond which the audibility zones follow the same sequence. The assumption of high temperatures in the upper air seems to offer the best explanation for the reflection of the sound waves back toward the earth at these regular intervals.

(3) The surface which separates the troposphere from the stratosphere is called the "tropopause" and its height varies from about 18 kilometers at the equator to about 6 kilometers over the poles. It is higher in summer than in winter and higher over anticyclones than over cyclones. Waves in the tropopause may induce waves along fronts in the troposphere and vice versa. The interrelation between these waves may be used in making longer range forecasts.

g. Turbulent layer near the ground.—(1) The ground acts as a wall disturbing greatly the general movement of the atmosphere and its vertical structure up to an altitude of 1,000 meters over flat country or above the oceans, and even more so in mountainous areas. The ground has both a mechanical and a thermal influence on the atmosphere.

(2) From the mechanical point of view, the friction of the air with the surface of the ground checks the winds and influences their direction; its irregularities cause turbulence, a state of movement subject to extremely rapid variations; obstacles create complex turbulent zones, causing vortices and noticeable vertical motions.

(3) From the thermal point of view, an excessive amount of heat is inducted into the layers of air near the ground by terrestial radiation, conduction, and convection during the day, and an unusually large amount of heat is transferred from these layers to the ground at night. For these reasons, the average lapse rate of 6° C./km. does not usually exist near the ground. Commonly during the day, enormous lapse rates exist near the ground, of several degrees per meter. At night when the ground cools much more rapidly than the atmosphere, the air near the ground becomes colder than the air above producing an increase of temperature with altitude. This lapse rate is called an "inversion" because the increase of temperature with altitude is inverse to the normal lapse rate encountered in the atmosphere.

(4) The phenomenon of inversion of temperature also frequently occurs in the free air above the surface of a cloud layer which, from the point of view of radiation, plays a role analogous to the ground. These inversions must not be confused with those of dynamic origin

which are produced when warm air overruns cold air, or when a sinking mass of air is heated by compression to the point where it becomes warmer than the air below. This latter type of inversion is called a "subsidence inversion." All properties acquired from the ground by the air are influenced by the activity within the layer near the ground. When the ground is hot, the moisture evaporated from the surface and the heat acquired by the lower layers of air are distributed aloft by turbulence. This is how tropical air masses acquire their large moisture and heat content. When the ground is colder than the air, it absorbs heat and moisture from the air. Consequently, polar air masses are relatively dry and cold.

h. Temperature and air masses.—The criteria used in determining the physical properties of air masses should, insofar as possible, be conservative and representative. A conservative property is one that changes little from day to day or from day to night. A representative report of a given property is one that is not influenced by local or natural terrain features and gives a true indication of that property in its normal relation to the air mass. One of the most important properties of an air mass is temperature because it indicates different air masses and the transport of energy, but it is not usually representative. Surface temperature may be influenced by radiation, conduction, and convection, all of which are continually changing. The result is that land observations of temperature are not generally reliable or representative. They are more reliable on cloudy than clear days and better on windy than calm days. Temperatures are never decisive for locating fronts except when systematically arranged. Maximum temperature is a conservative element in summer and very useful. This is not true for minimum temperature. The increase in temperature during the day is small after the night inversion temperature has been reached. Maximum temperature is largely determined by the temperature of the free atmosphere, especially when inversions develop during the night and disappear during the day at inland stations. A representative surface temperature may be obtained by projecting the temperature curve of the free atmosphere down to the surface. When there is a front present, no such extrapolation is possible. As a whole, temperature is a poor element to use in locating fronts unless it is used with extreme care.

i. Temperatures over the ocean.—The ocean is a powerful absorbing body and evaporation takes place almost immediately upon the reception of heat by radiation. Only the fresh water evaporates, thereby leaving the salts and increasing the density of the surface layer. Being heavier, it sinks and causes more cold water to be

brought to the surface. The specific heat of the ocean is several thousand times that of the air. The result of the above two effects is that there is practically no diurnal variation of ocean surface temperature. The maximum is about ½° C. The sea surface controls the air temperature so there is little diurnal variation of temperature over the ocean. During the day, the air aloft is heated by solar radiation and the air at the surface is kept cool by the water. At night, the air aloft loses its heat by radiation while the temperature of the air near the surface is kept constant by the water. For these reasons, the air tends to rise more readily over the ocean at night than during the day with the result that there is maximum cloudiness during the

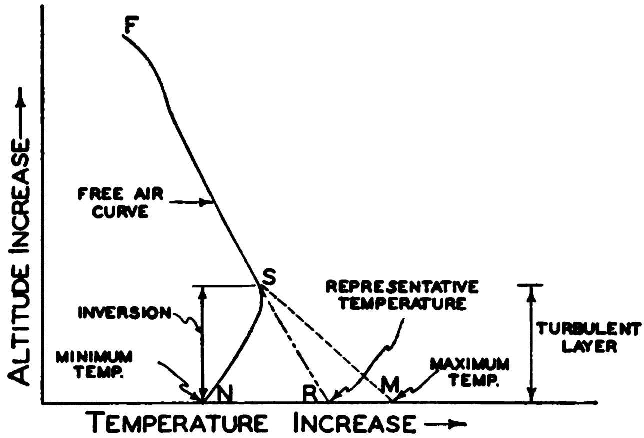


FIGURE 19.—Diurnal temperature variation over land.

night and minimum cloudiness during the day. The reverse is true over land.

j. Dew point temperature.—(1) The "dew point" is the temperature to which the air must be cooled in order to become saturated. It is always less than the temperature unless the air is saturated. It is a conservative element until condensation or evaporation takes place. It is used a great deal in the United States to identify air masses, locate fronts, and in relation to fog.

(2) In fog, the air is saturated or very nearly so and the dew point and temperature must be the same or approximately the same. The less the difference between dew point and temperature, the more the probability of fog. Dew point increases during and after a rain or when the air crosses a wet area or large body of water. Hence, in the use of dew point, local influences must be taken into account, especially evaporation areas. A true continental air changes dew point very slowly.

23. Humidity.—*a. Water in the atmosphere.*—Water exists in the atmosphere in three states:

Solid	Snow, hail, ice crystal clouds.
Liquid	Water clouds, rain.
Gaseous	Water vapor.

(1) Water is visible in the atmosphere only when it is in the liquid or solid state. In the vapor state, it is invisible like other gases. The steam that may be seen escaping from the top of a boiler is not water vapor but condensed water in fine droplets. Clear air near the earth always contains water vapor as shown by the dewdrops which are deposited on plants on clear nights.

(2) Like gas, water vapor possesses an elastic force. It is this force that moves the pistons of steam engines. In the atmosphere the elastic force of water vapor, called "vapor pressure," is of a much smaller order—a few millimeters of mercury. The humidity of the air may be defined by the quantity of water vapor which is contained in a given volume of moist air; for example, a cubic meter. This is called absolute humidity. It is useful to know that the number of grams of water vapor contained in a cubic meter of air is almost equal to the vapor pressure expressed in millimeters of mercury. A cubic meter contains then, ordinarily, several grams of water vapor.

b. Composition of the atmosphere.—The atmosphere consists roughly, by volume, of 78 percent nitrogen, 21 percent oxygen, with carbon dioxide, hydrogen, and the rare gases argon, neon, helium, krypton, and xenon, forming about 1 percent of the atmosphere. There are minor impurities and varying percentages of water vapor. Apart from the water vapor, the other constituents are present in such unvarying proportions, except for local pollution due to factory chimneys and similar sources, that we may treat dry air as a uniform mixture and leave entirely out of consideration all questions of its constitution. The water-vapor content never exceeds 4 percent of the total atmosphere. These gases do not form a single chemical substance but exist as a mixture in the space surrounding the earth. The composition of the atmosphere is remarkably constant up to very great heights, at least to 300 or 400 miles. The composition of the atmosphere at high altitudes has been determined by spectral analysis of the light from auroras and shooting stars.

c. Condensation of water vapor.—(1) If dry air is enclosed in a bell jar containing a panful of water, the surrounding temperature being maintained constant, the water evaporates and the air becomes humidified or moist. But there comes a time when the air becomes sat-

urated with moisture, evaporation ceases, and the content of water vapor in the air does not increase. The pressure corresponding to this is called the "saturation water vapor pressure" at the given temperature. The saturation vapor pressure increases rapidly with temperature; that is, the warmer the air, the more it is able to absorb water vapor before becoming saturated. Thus, from 6½ millimeters at 5° C., the saturation vapor pressure increases to 13 millimeters at 15° C., 24 millimeters at 30° C., to attain a vapor pressure of 1 atmosphere (760 millimeters) at the boiling temperature of water (100° C.).

(2) Consider a mass of nonsaturated moist air having a vapor pressure of 13 millimeters at 30° C., that is, containing 13 grams of water vapor per cubic meter of air, and assume this air to be cooled. When a temperature of 15° C. is reached, the air will be saturated, since at this temperature it can only hold 13 grams per cubic meter. Similarly, if we continue to cool it below 15° C., part of the water vapor condenses, the air being constantly at its limit of saturation. Thus, if a final temperature of 5° C. is attained, at that moment there can exist no more than 6½ grams of water vapor per cubic meter and the air contains $13-6.5=6.5$ grams of liquid water per cubic meter.

(3) The condensation of water vapor caused by the cooling of a mass of moist air explains the formations of clouds, fog, and mist. This process is familiar to all. Everyone has observed in winter that steam is deposited on the inner surface of windows, cooled by the exterior air, in a warm room. The inner air is not saturated, but it becomes so when cooled by contact with the window.

(4) When the temperature of saturated air becomes less than 0° C., condensation no longer occurs in the form of water but in the form of ice. Thus, on cold nights, ice crystals and not water droplets are deposited on the interior surfaces of windows.

d. Hygrometric state (relative humidity).—(1) The physiological sensation of dryness, or of humidity, does not depend upon the quantity of water vapor in the air (absolute humidity) but upon the fact that this air is more or less removed from the saturated state. Assume that outside air has been admitted to a heated room. When the air has reached the temperature of the room (20° C., for example), one gets an impression of dryness which does not exist when the air is at the outside temperature (5° C., for example). However, the content of water vapor (5 grams per cubic meter) has not changed. While the temperature was 5° C., the vapor pressure of 5 millimeters was very near its saturation value (6½ millimeters). It was, however, very distant at 20° C., where the saturation vapor pressure has a value of 17½ millimeters. The degree of saturation of the air is determined

by the ratio of the actual vapor pressure to the maximum possible vapor pressure at a given temperature. The degree of saturation is also approximately the ratio of the actual water vapor contained in a cubic meter of air to the maximum possible quantity. In order to avoid decimals, this ratio is multiplied by 100 and the result, expressed in percent, is called the relative humidity. Thus, in the preceding example, the hygrometric state or degree of saturation of the exterior air at 5° C. and a vapor pressure of 5 millimeters was $\frac{100 \times 5}{6.5} = 78$ percent. This type of air seems humid. When the same mass of air is heated to 20° C. it contains the same quantity of water vapor but its relative humidity is $\frac{100 \times 5}{17\frac{1}{2}} = 28$ percent. This type of air seems dry.

(2) Modern air conditioning employs the principles enumerated above. If the air is hot and very moist the air-conditioning engineer must devise a method to take water out of the air as well as reduce the air temperature; otherwise, moisture from the body would not evaporate and an observer would feel uncomfortable. This requires a refrigeration system which is the most expensive type of air-conditioning installation. If the air is hot and dry, the introduction of moisture will absorb heat from the air and cool it, but still, the relative humidity will be low enough for comfort. This is why the residents of Arizona may air-condition their homes on a hot summer day by simply hanging moist burlap over the open windows. It is readily seen that air conditioning in the summer time is most expensive in areas frequented by tropical air masses because they are warm and moist. In the winter, the problem is usually one of introducing moisture into the air to make up for the dryness caused by local heating systems. Moist cool air is more comfortable than relatively dry cool air. The same problems must be met in the cabins of air liners with the additional requirements of supplying sufficient oxygen at a reasonable air pressure.

(3) Relative humidity is not a conservative element because it depends upon saturation vapor pressure which is a function of temperature. Consequently, it varies with the diurnal change in temperature and in convections. It is of no use in identifying air masses but is used in many ways, especially in relation to fog and the location of fronts.

(4) When the relative humidity is zero, the air is completely dry. During the Santa Ana winds in Southern California, the relative

humidity approaches this limit, but it is not so much that the air has been deprived of its water vapor but that the temperature is relatively high, that the water vapor is very far from condensation.

(5) When the relative humidity is 100 percent, condensation of the water vapor occurs. This is seen in foggy weather or in the clouds.

(6) Absolute humidity is not a conservative element because it changes with the expansion and contraction of air and is not used in air-mass analysis.

e. Humidity instruments.—(1) Instantaneous humidity values are determined by a hygrometer or psychrometer. A psychrometer con-

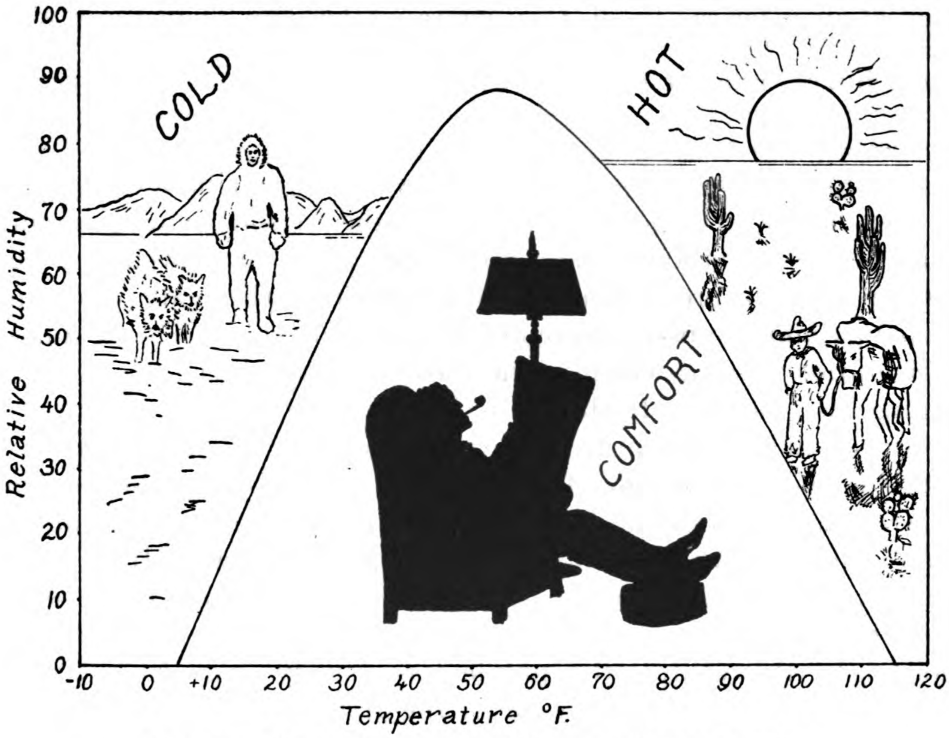


FIGURE 20.—Temperature versus humidity ranges of human comfort.

sists of two thermometers, one of which has the bulb enclosed in saturated gauze. Free air is rapidly passed by these thermometers so that the dry bulb gives a representative free air temperature while the wet bulb is cooled by the evaporation of moisture from the gauze. The rate of evaporation depends upon the humidity of the air. The difference in temperature between the wet and dry bulbs is used along with the free air temperature and pressure as arguments for entry into previously constructed psychrometric tables. Relative humidity, dew point, and vapor pressure are given in the tables.

(2) A hygrometer is actuated by the expansion and contraction of a strand of human hairs with changes in the humidity of the air. A

hand calibrated with a dial gives the current value of the relative humidity.

(3) A continuous humidity record is obtained from a hygrograph. This instrument is actuated by a strand of human hairs like the hygrometer but instead of indicating on a dial, a record is made by a pen on a sheet attached to a rotating drum. (See fig. 14.) The recorded values are those of relative humidity. The most practical humidity recording instrument yet developed depends upon the principle given above. The change in the electrical conductivity of certain salt solutions with changes in humidity is being used to some extent, especially in radio meteorographs. Hair elements have considerable lag and become useless at low temperatures.

f. Specific humidity "q" and mixing ratio "w."—(1) The specific humidity q is defined as the ratio of the mass of water vapor in a sample of moist air to the mass of the sample, $q=\frac{5}{8}\frac{e}{p}$, e being the vapor pressure and p the total air pressure. The total air pressure is the sum of the pressure of the dry air and the vapor pressure. Mixing ratio w is the mass of water vapor in a sample of air to the mass of dry air in the sample; w is expressed in grams per kilogram of dry air. Approximately, $w=\frac{5}{8}\frac{e}{p_d}$ where p_d is the pressure of the dry air. This equation shows that w is independent of temperature, therefore unlike relative or absolute humidity, and remains unchanged during vertical motions in the atmosphere, providing they take place without evaporation or condensation. Even in very moist air, the difference between q and w is too small to warrant consideration in forecasting practice. However, w is sometimes used in preference to q where exact computations are necessary as it simplifies some of the formulae frequently utilized in determining the thermal state of the atmosphere. Both terms are given because some meteorologists refer to q and others to w, but for all practical purposes they are synonymous.

(2) Since q and w do not vary with temperature it makes no difference whether it is day or night, whether a given mass of air is at 20,000 feet or at sea level, q and w remain the same unless moisture has been added to or taken from the air. Therefore, specific humidity and mixing ratio are conservative air-mass properties and are suitable for use in identifying the various air masses. For example, the average value of w, in winter, in Tg air at Broken Arrow, Okla., is 11.8g./kg. and at Royal Center, Ind., it is 11.3g./kg. By noting the reported values of w, the forecaster may not only determine the limits of the

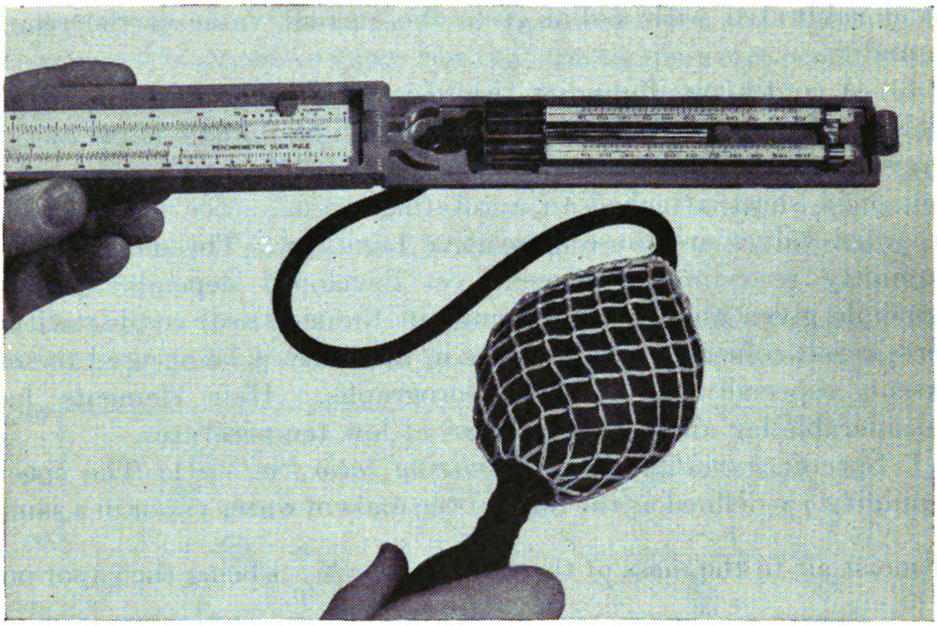


FIGURE 21.—Hand-aspirated psychrometer.

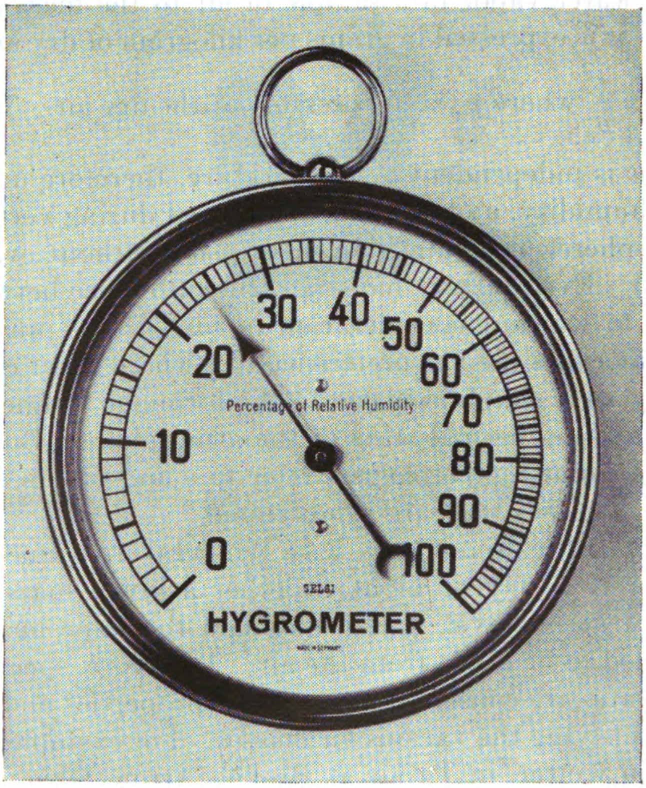


FIGURE 22.—Hygrometer.

various air masses but he may also follow their trajectories as they move over the surface of the earth.

(3) Humidity is an element, the importance of which cannot be overemphasized. The distribution of humidity values is important for the location of fronts, in relation to fog, icing conditions, and the distribution of clouds and precipitation.

SECTION IV

AIR MOVEMENTS

24. General.—The wind is air in motion. The general movements of the air are almost horizontal, the variance usually being not more than a few degrees. The vertical components are of extreme importance and are discussed later.

25. Surface Winds.—The direction of the wind is that direction from which it is moving; that is, a west wind is a wind blowing from the west. Surface winds are reported to 16 points of the compass in airways reports. Mariners usually report the wind to 32 points of the compass because wind direction over the ocean is more representative than over land. Wind direction is obtained by means of a wind vane. Wind velocity is determined by anemometers and by estimation.

a. There are two types of anemometers; rotating anemometers which measure the velocity of the wind by the rate of rotation of metal cups, and pressure anemometers which utilize the difference between the dynamic and static pressures to determine wind velocity. These instruments are calibrated to give wind velocity in miles per hour and are so reported at airways stations.

b. Estimation is made from the effect wind action has on various objects. Wind velocity determined this way is measured according to the Beaufort scale which was introduced by Admiral Beaufort in 1806. The Beaufort scale is used internationally and all winds are

converted to Beaufort numbers before they are plotted on weather maps. Wind velocity and direction vary with the distance above the

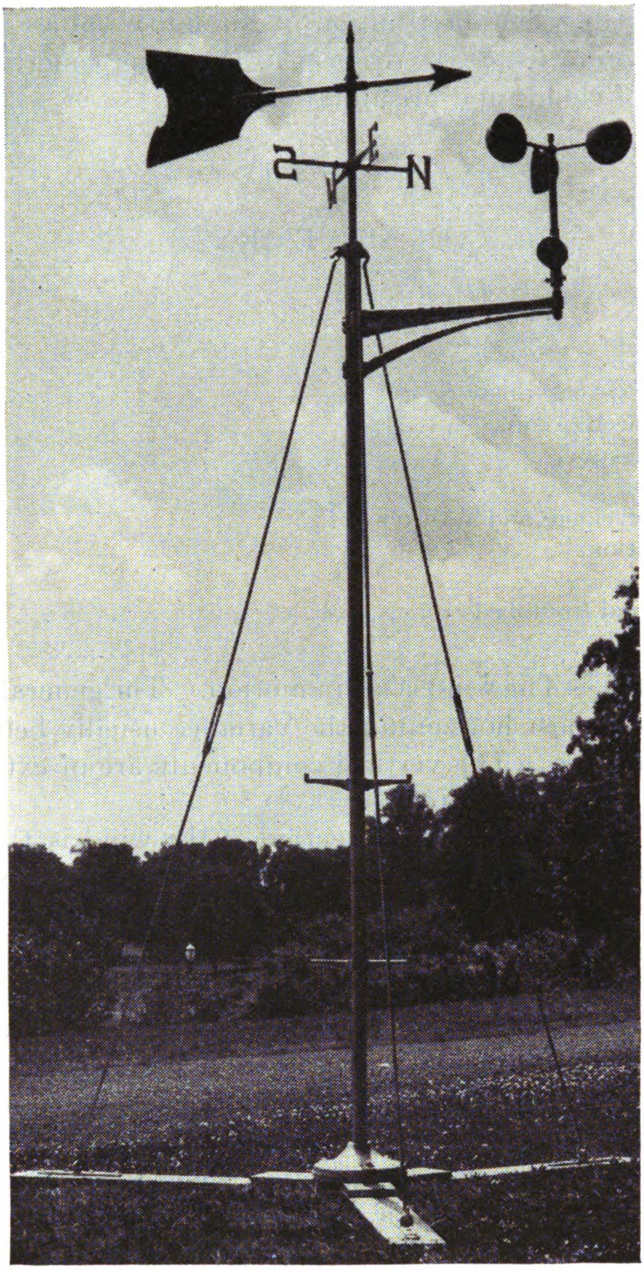


FIGURE 23.—Anemometer and wind vane.

ground, variation being particularly rapid near the ground. The wind velocity as given in the Beaufort scale shown below is for winds at the standard anemometer elevation of 20 feet above the ground.

Beaufort scale of wind force with specifications and velocity equivalents

Beaufort number	General description	Specification	Limits of velocity 6 meters above level ground		
			Meters/sec.	Km/hr.	Miles/hr.
0	Calm	Smoke rises vertically	Less than 0. 4	Less than 1. 4	Less than 1
1	Light air	Wind direction shown by smoke drift but not by vanes	0. 4– 1. 5	1. 4– 5. 4	1– 3
2	Slight breeze	Wind felt on face; leaves rustle; ordinary vane moved by wind.	1. 6– 3. 3	5. 8–11. 9	4– 7
3	Gentle breeze	Leaves and twigs in constant motion; wind extends light flag.	3. 4– 5. 4	12. 2–19. 4	8–12
4	Moderate breeze	Raises dust and loose paper; small branches are moved	5. 5– 7. 9	19. 8–28. 4	13–18
5	Fresh breeze	Small trees in leaf begin to sway	8. 0–10. 7	28. 8–38. 5	19–24
6	Strong breeze	Large branches in motion; whistling in telegraph wires	10. 8–13. 8	38. 9–49. 7	25–31
7	Moderate gale	Whole trees in motion	13. 9–17. 1	50. 0–61. 6	32–38
8	Fresh gale	Breaks twigs off trees; generally impedes progress	17. 2–20. 7	61. 9–74. 5	39–46
9	Strong gale	Slight structural damage; chimney pots removed	20. 8–24. 4	74. 9–87. 8	47–54
10	Whole gale	Trees uprooted; considerable structural damage	24. 5–28. 4	88. 2–102. 2	55–63
11	Storm	Very rarely experienced; widespread damage	28. 5–33. 5	102. 6–120. 6	64–75
12	Hurricane		Above 33. 5	Above 120. 6	Above 75

26. Winds aloft.—*a.* Upper winds are obtained by following the ascent of a hydrogen filled balloon by an instrument called a "theodolite." The azimuth and elevation of the balloon are recorded at one minute intervals, and knowing the rate of ascent of the balloon, it is possible to determine the wind direction and velocity aloft. There are about 100 stations in the United States which make winds-aloft observations every 6 hours. They determine the wind for each 1,000-

FIGURE 24.—Theodolite and winds aloft balloon.

foot level above the station and transmit these data over the teletype and radio networks.

b. When two theodolites are used, the rate of ascent of the balloon need not be known and more accurate observations are possible.

c. When a balloon enters some obstruction to vision such as clouds or dust, or when high winds carry it out of visible range, the theodolite becomes useless. These are just the times when upper air observations are most desirable. This difficulty has been overcome by the use of balloons with automotic radio transmitters attached. A

directional receiver on the ground may follow these instruments in any kind of weather except severe thunderstorms. The use of this method is limited due to technical difficulties.

d. The determination of winds aloft from ships at sea is difficult due to the movement of the ship. Special theodolites are required in this work.

e. Winds at cloud levels may be determined by noting the direction and rate of motion of the clouds in relation to the ground by means of a nephoscope. The direction and rate of motion of cloud shadows on the ground may be estimated from the air.

f. When the ground is visible, the pilot can determine wind direction and velocity by calculating the drift of the airplane. At sea this is done by dropping smoke bombs that will float on the surface of the water. When the ground is not visible, the pilot may estimate the wind direction and velocity by noting the shape of the clouds and the motions within them.

g. Surface winds at airdromes are indicated by wind socks, wind vanes, anemometers, wind tees, and smoke boxes. Away from the airdrome some of the various things that indicate the surface wind are smoke columns, water waves, dust, windmills, clothes on clotheslines, movement of grass, brush, and trees, and frequently the orientation of grazing stock.

h. Finally, it is possible to determine the winds aloft from the distribution of the barometric pressure.

27. Wind and atmospheric pressure.—The atmosphere may be regarded as a huge engine which converts heat energy from the sun into kinetic energy (energy of motion). Due to the relative position of the earth to the sun, much more heat is received by the atmosphere near the equator than at the poles. When air is heated it expands so that a cubic foot of air at the poles will weigh more than the same volume of air at the equator. The result is that for any intermediate volume of air there would be a greater pressure on the side nearest the pole than on the equatorial side if the earth did not rotate. Therefore, a nonrotating earth would have continuous north winds at the surface in the Northern Hemisphere with the air rising at the Equator, returning aloft, and sinking at the poles. These movements would be the result of differences in pressure caused by differences in temperature. However, the earth does rotate, and its rotation originates forces which deflect the winds in such a manner that the deflective force tends to balance differences of pressure.

28. The earth's deflective force.—*a.* Within the visible range of the North Pole, the surface of the earth is, for all practical purposes,

a flat disk rotating counterclockwise about the pole. This rotation may be represented on a small scale by rotating the circular piece of paper shown in figure 25. Assume the point of a pencil to be placed at the center *P* and drawn along a straight edge toward a stationary object *O* outside the rotating paper. The curve *PEO* represents the trace of the pencil, the portion *PE* being curved due to the rotation of the paper. To an observer standing on the rotating paper who could not see beyond its edge, it would seem that the pencil point was continually curving off to the right, while to an observer standing outside the paper, it would appear that the pencil moved in a straight line. Both observations would be correct. One is caused by relative

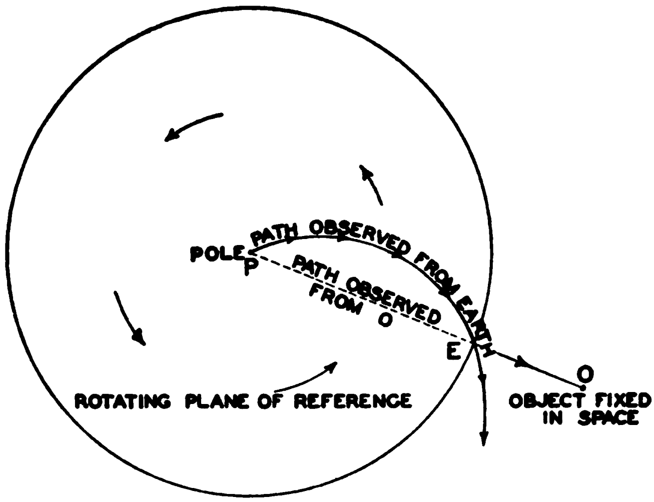


FIGURE 25.—Principle of the earth's deflective force.

motion and the other by motion in space. The acceleration which apparently deflected the pencil to the right has the value $2V\omega$, where V is the velocity of the pencil point and ω is the angular velocity of the paper. In terms of wind and the earth, V represents wind velocity and ω the angular velocity of the earth's rotation. Therefore, the acceleration of the earth's deflective force at the pole is $2V\omega$. This same deflecting force acts at all latitudes in an amount which is directly proportional to the sin ϕ, where ϕ is the latitude. Hence, the earth's deflective force may be represented by F in the equation

$$F=2V\omega \sin \phi.$$

This force is frequently called the "coriolis force." It acts upon all objects that move over the surface of the earth. It affects the motion of ocean currents, rivers, and projectiles.

b. When the wind starts to blow toward an area of lower pressure, the earth's rotation forces it more and more to the right until the deflecting force is directly opposed to the direction of the most rapid rate of decrease of pressure. This latter direction is called the "pressure gradient." The ultimate wind direction and speed will be determined when these two forces are just balanced. This happens very readily in the atmosphere and the wind direction is perpendicular to these two forces. This wind is called the "geostrophic wind" and is represented by the V in the equation

$$V = G/2\rho\omega \sin \phi$$

where ρ is the density of the air and G is the pressure gradient. ω and $\sin \phi$ are almost constant in any small area, hence the geostrophic wind is directly proportional to the pressure gradient.

c. From the above it is seen that all winds in the Northern Hemisphere are deflected to the right by the earth's deflective force. The reverse is true in the Southern Hemisphere. Also the deflective force has continuously acted perpendicular to the wind direction and therefore has not affected the speed of the wind. The wind speed is almost purely a function of the pressure gradient at a given latitude, the only variant being density, which is very small.

29. The field of pressure.—The field of pressure is represented on a weather map by "isobars" which are lines drawn through points of equal pressure. Isobars are normally drawn for all values of pressure in millibars divisible by 3. Since the reported pressures are sea-level pressures, the isobars represent the field of pressure at sea level. For high-altitude stations such as Salt Lake, it is frequently more desirable to draw isobars for some higher elevation, usually 5,000 feet at this station. A map drawn in this fashion will show centers of high and low pressure, wedges which represent ridges of high pressure, and troughs or valleys of low pressure. Since wind velocity is directly proportional to the pressure gradient and the pressure gradient has its greatest value where the isobars are closest together, it is apparent that the geostrophic wind is strongest where the isobars are closest together and that it is least where the isobars are farthest apart. Friction between the air and the surface of the earth decreases the wind velocity as the surface is approached. The friction effect extends up to about 2,000 feet so that is where the geostrophic wind attains its true value as represented by the isobars. Therefore a glance at the weather map immediately gives the observer a picture of the distribution of the wind direction and speed at 2,000 feet above sea level over the entire area covered by a weather map.

Local obstructions, mountains, valleys, and the sea breeze often cause the actual wind to be at variance with the geostrophic wind; however, the geostrophic wind is a very good approximation. It always blows at right angles to the pressure gradient and, therefore, blows along the isobars in such a direction that lower pressure is to the left. This has long been known and used. This principle is given in Buys-Ballot's law which may be expressed for the Northern Hemisphere as follows: "Put your back to the wind and lower pressure is to your left." The reverse is true in the Southern Hemisphere. Pilots use this rule continually to keep informed as to the relative location of low-and high-pressure areas.

30. Effect of friction.—*a.* Friction between the air and the surface of the earth not only cuts down the wind velocity but it also

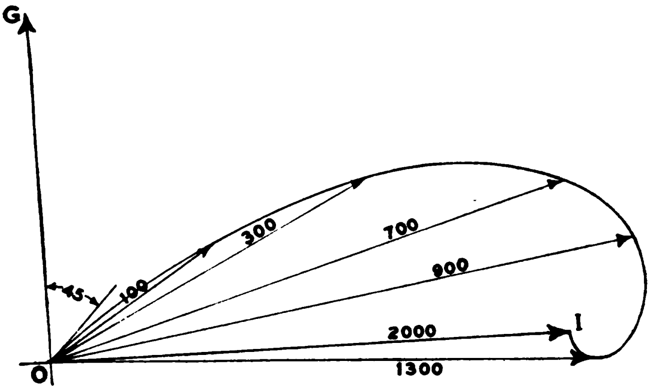


FIGURE 26.—Variation of wind with altitude; Ekman spiral.

deflects the wind to the left of its true direction as shown by the isobars.

b. From the geostrophic wind equation, it is seen that when V is decreased for a given spacing of the isobars, the force of the pressure gradient exceeds the deflective force. The wind then would tend to flow in the direction of the pressure gradient which is to the left of the true geostrophic direction. Depending upon the wind velocity and the roughness of the surface, the deflection varies from 10° to 30° and is more over land than over water. Reported surface wind speeds over land have a value of about 40 percent of their true or geostrophic value, while over the ocean their value is about 70 percent of the true value.

c. How the effect of friction varies with altitude is shown in figure 26. O represents a point at the surface of the ground, OI an isobar, I being at 2,000 feet, OG the pressure gradient and the vectors to the spiral represent wind direction and speed at the elevations indicated. The wind velocity at the ground is O, and just above the surface the

angle of deflection is 45° to decrease to 0° at 2,000 feet. The increasing length of the vectors as the elevation is increased shows the increase in wind speed up to the 2,000-foot level.

d. The above information together with the Buys-Ballot law is of tremendous importance to anyone drawing a weather map. For example, if a station reports a south wind of force 4 on the Beaufort scale (13 to 18 m. p. h.) and a pressure of 1,017.7 millibars of mercury, the forecaster knows that the 1,017 isobar runs about 20° to the right of north and is located a short distance to the left of the station. Knowing the variation of wind direction and velocity with altitude is also of great importance to the pilot. He can seek the level of strongest tail winds or least head winds. If the wind is on his nose, he goes down, if it is on his tail, he goes up.

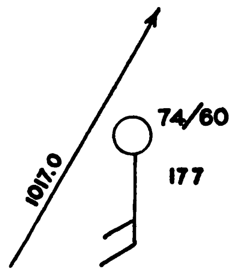


FIGURE 27.—Location and orientation of an isobar.

e. Friction and obstructions cause turbulence or "bumpiness" and interchange between air layers. This tends to distribute moisture, dust, and smoke evenly throughout the turbulent layer. Sufficient change in wind velocity between air layers may cause friction and turbulence even at high levels. The critical value of the vertical velocity gradient is 1m/s/100 m.

f. The geostrophic wind blows along straight isobars and assumes no curvature in the direction of motion of the wind. This assumption gives good practical results anywhere except where the curvature of the isobars is extreme.

31. Circulation in cyclones and anticyclones.—*a.* In curvilinear motion, the centrifugal force, $\rho V^2/r$, enters where r is the radius of curvature, and acts toward the convex side of the isobars. Add this term to the above equation for the geostrophic wind and the equation becomes

$$G/\rho = 2V\omega \sin \phi - V^2/r$$

for an anticyclone or high-pressure area and

$$G/\rho = 2V\omega \sin \phi + V^2/r$$

for a cyclone or low-pressure area. These equations state that for an anticyclone the pressure gradient is balanced by the deflective force minus the centrifugal force, and that for a cyclone the pressure gradient is balanced by the deflective force plus the centrifugal force.

b. Consideration of the equation for an anticyclone shows that the equation has no meaning when the deflective force is equal to zero and since this force is proportional to the sin of the latitude, anticyclones cannot exist at the Equator. V in these equations is called the

"gradient wind," and the equation is called the "gradient wind equation."

32. General circulation.—*a.* The maximum effect of solar radiation is felt in the Tropics. The circulation established is such that the air at the surface tends to move toward the Equator and the air aloft toward more northerly latitudes. Deflective effects of the earth's rotation change the northward moving currents to eastward moving ones, and the southward moving currents to westward moving ones. This effect produces trade winds at the surface which form a great westward moving current near the Equator and the antitrades aloft. At about 30° N. and S. the antitrades appear as eastward moving currents at the ground, having cooled sufficiently to sink to the earth in a high-pressure area established there. The westerly

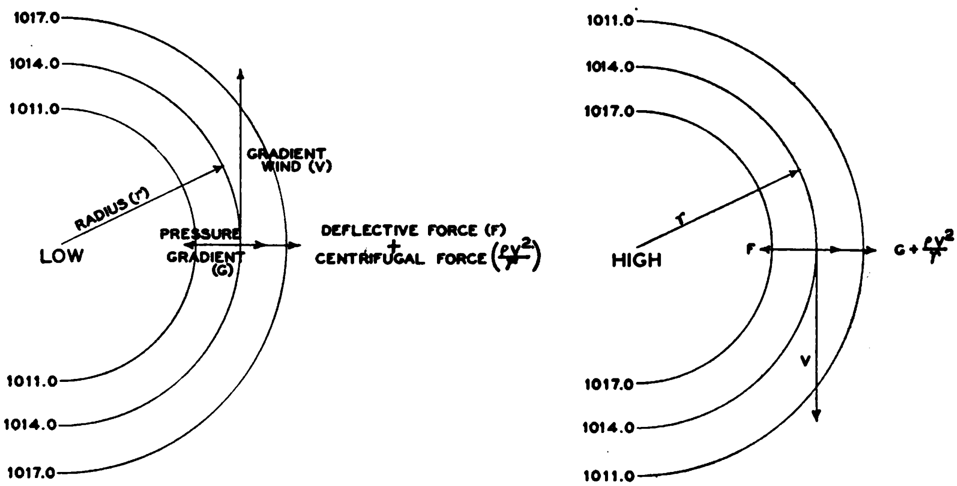


FIGURE 28.—Balance of forces for horizontal, frictionless, curvilinear flow in cyclones and anticyclones on the Northern Hemisphere.

winds on the poleward side of these anticyclones form the prevailing westerlies of the middle latitudes. These belts of high pressure are called the "subtropical anticyclones." We may call the circulation of the trade-wind belt a thermodynamically direct one because the circulation takes place in accordance with the principle of the circulation of fluids. That is, the flow is from the cold source toward the warm source at the surface and from the warm source toward the cold source aloft.

b. The circulation of the polar caps is a thermodynamically direct one although it is not as well developed as that of the subtropics. It is produced roughly as follows: over the poles there is a sinking of cooling air masses which tend to move toward the Equator, being deflected in accordance with the effect of the earth's rotation on the Northern Hemisphere. The air masses move southward and are

deflected to westward moving ones. Any regular southward movement ceases at about 60° N. A part of the current is heated sufficiently to return northward in the upper branch of this circulation, whereas the remainder moves southward in irregular outbreaks of cold polar air constituting cold waves. The average winds in the middle latitudes are westerly. Therefore, at about 50° N. to 60° N., an atmospheric discontinuity tends to arise between the cold easterly currents of polar origin and the warm westerly winds of the middle latitudes. This discontinuity surface extends around almost the entire earth in these latitudes and has been termed the "polar front."

33. Cyclone families.—The outbreaks of cold air from the north favor a northward movement of warm air to their east with the establishment of a trough of minimum pressure between the two currents.

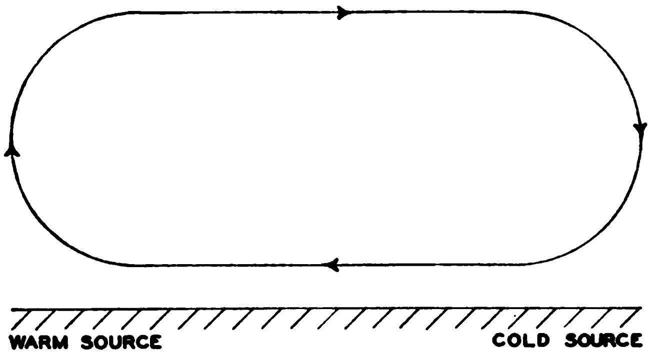


FIGURE 29.—The circulation principle.

It is in such troughs that the interactions known as "cyclone families" occur. The cyclone families are the migratory low-pressure areas of the middle latitudes. They are accompanied by the migratory anticyclones of this belt. The outbreaks of polar air are usually of great depth and tend to compensate both the accompanying northward moving current of warm air and the normally uniform poleward movement of the middle latitudes. These cold currents may, at times, occupy the entire region below the tropopause and attain velocities of 100 miles per hour. Along the polar front (fig. 30) may be seen a series of wave disturbances constituting a cyclone family of the middle latitudes. At the center of the figure, an outbreak of polar air is shown which has moved southward far enough to enter the trade wind circulation. If average isobars are drawn in winter on the Northern Hemisphere, persistent HIGHS and LOWS, the semipermanent anticyclones and cyclones appear. The land and water distribution determines their position to some extent. For example, over the extremely cold continental areas there are areas of persistent high pressure during this season of the year. This is illustrated in figure 31. The regions

of persistent low pressure occur over the North Pacific Ocean and over the North Atlantic Ocean and are called the "Aleutian" and "Icelandic" Lows respectively. At about the same latitudes, the continental high-pressure areas are known as the "Canadian" and "Siberian" HIGHS. The semipermanent anticyclones in the subtropical high-pressure belts, south of the semipermanent Lows are known as the "Pacific" and "Bermuda" HIGHS.

34. Frontogenesis and frontolysis.—"Frontogenesis" is the creation or strengthening of fronts generally brought about through the horizontal convergence of air currents possessing widely different properties. "Frontolysis" is the destruction of fronts generally brought about by horizontal divergence at the discontinuity zones.

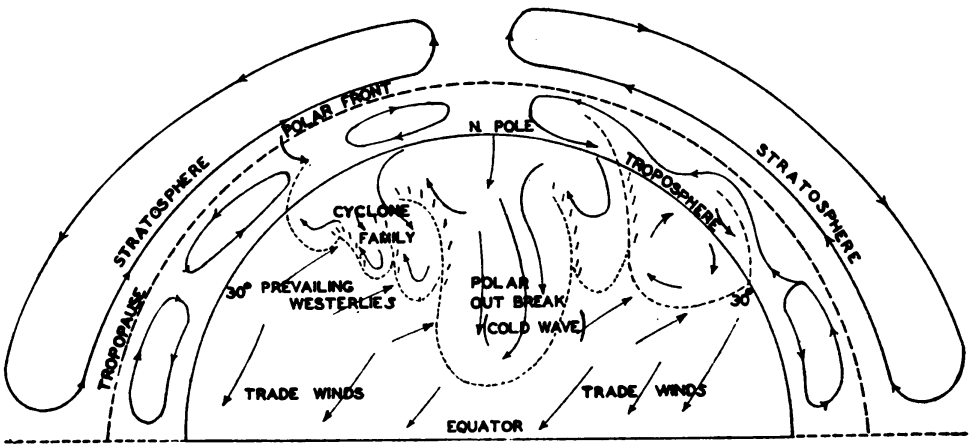


FIGURE 30.—Schematic diagram of general circulation in the atmosphere.

Over the North Atlantic Ocean, convergent flow between polar and tropical air masses is most apt to occur between the Bermuda HIGH and the Canadian HIGH and the Icelandic LOW. This area of convergent flow constitutes the breeding place for the extra-tropical cyclones which are the result of wave formations upon the fronts developing in the frontogenetic region. Over the Pacific Ocean, the frontogenetic region lies between the Pacific HIGH, the Siberian HIGH, and the Aleutian LOW. It is seen then that the major atmospheric disturbances originate off the southeast coast of Asia and North America. The regions of divergent flow between polar and tropical currents as indicated in figure 31 constitute areas where no cyclogenesis takes place. Frontal systems moving into areas of divergent flow tend to dissipate. Northwestern Europe and the Pacific Coast of North America are the principal areas of frontal destruction.

35. Vertical motions.—It has long been known that vertical motions in the atmosphere are of great significance in that practically

all precipitation may be ascribed to the condensation brought about through expansional cooling of rising air. These motions cause clouds, rain, snow, hail, and sleet. The most rapid changes in temperature or moisture result from the vertical motions in free air. The amount of precipitation possible through the mixing of currents of air possessing different temperature and moisture characteristics is negligible. The theory of fronts and air masses is based upon atmospheric dis-

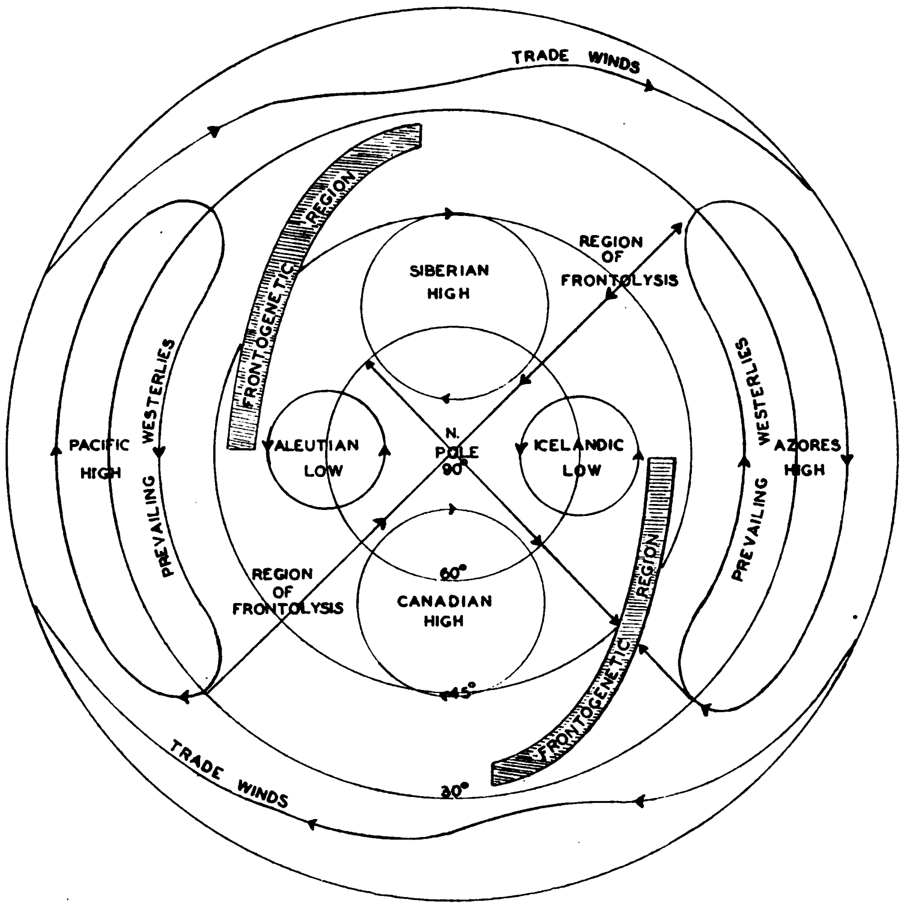


FIGURE 31.—General circulation on the Northern Hemisphere in winter.

continuities, which are simply zones of rapid transition of the various meteorological elements. Observational material shows that these zones of transition are comparatively free from large scale mixing, the individual large scale air currents flowing side by side or above one another without appreciable mutual interchange. One great factor which tends to aid or hinder vertical motions is the stability of the atmosphere.

a. Movement of isolated particles of air.—The whole question of whether restoring or disturbing forces will be caused by a movement

depends upon whether, after the motion, the temperature of the moving particle of a volume of air is colder or warmer than the air layer through which it is passing. The truth of this is apparent for two reasons:

(1) The buoyant force of the surrounding atmosphere on the moving air is, according to Archimedes' Principle, equal to the weight of the displaced volume of the surrounding air. This relation is identical to the buoyant force on a piece of wood in water where the upward force equals the weight of the water displaced by the wood. Obviously then, if the moving volume of air is heavier than its surroundings, the net force acting on it will be to retard a rise or to cause a descent. If the moving volume is lighter, it will start to rise or stop descending.

(2) The weight of air per unit volume depends on pressure, temperature, and humidity. The latter, insofar as density calculations are concerned, is negligible in comparison with the temperature effect. Due to the elasticity of air, the rising or falling air particles are always at the same pressure as the surrounding air layers. Hence the deciding feature is the temperature. If warmer than the air layers passed through, the moving particles will be lighter and tend to rise, and if colder, they will be heavier and tend to descend.

b. Adiabatic changes in temperature.—(1) On rising, any air particle passes through a region of continuously falling pressure due to the decrease in the weight of the atmosphere above it. The expansion that results from the decrease in pressure is accompanied by a fall in temperature. Conversely, a descending particle is subjected to compression from constantly increasing pressure and is consequently warmed. If, at the same time that the temperature changes due to fluctuating pressure, heat should be lost to the surrounding air or to interstellar space, almost any temperature change could result. Actually comparatively little heat is so lost during rapid changes of altitude and for relatively slow ones only a small error will be introduced by assuming that the particle is thermally insulated. When temperature changes are effected in such a manner, that is, with no exchange of heat to or from the air mass considered, the process is termed "adiabatic." An unsaturated air particle rising or descending adiabatically will change its temperature about 1° C./100 m., 10° C./km., or 3° C./1,000 ft. This rate of change of temperature with height during adiabatic movements of unsaturated air is known as the "dry adiabatic lapse rate." Unsaturated air is referred to as "dry air." On temperature height and temperature-pressure (T–P) diagrams (adiabatic charts) the lines along which the lapse rate is adiabatic are called "dry adiabatics."

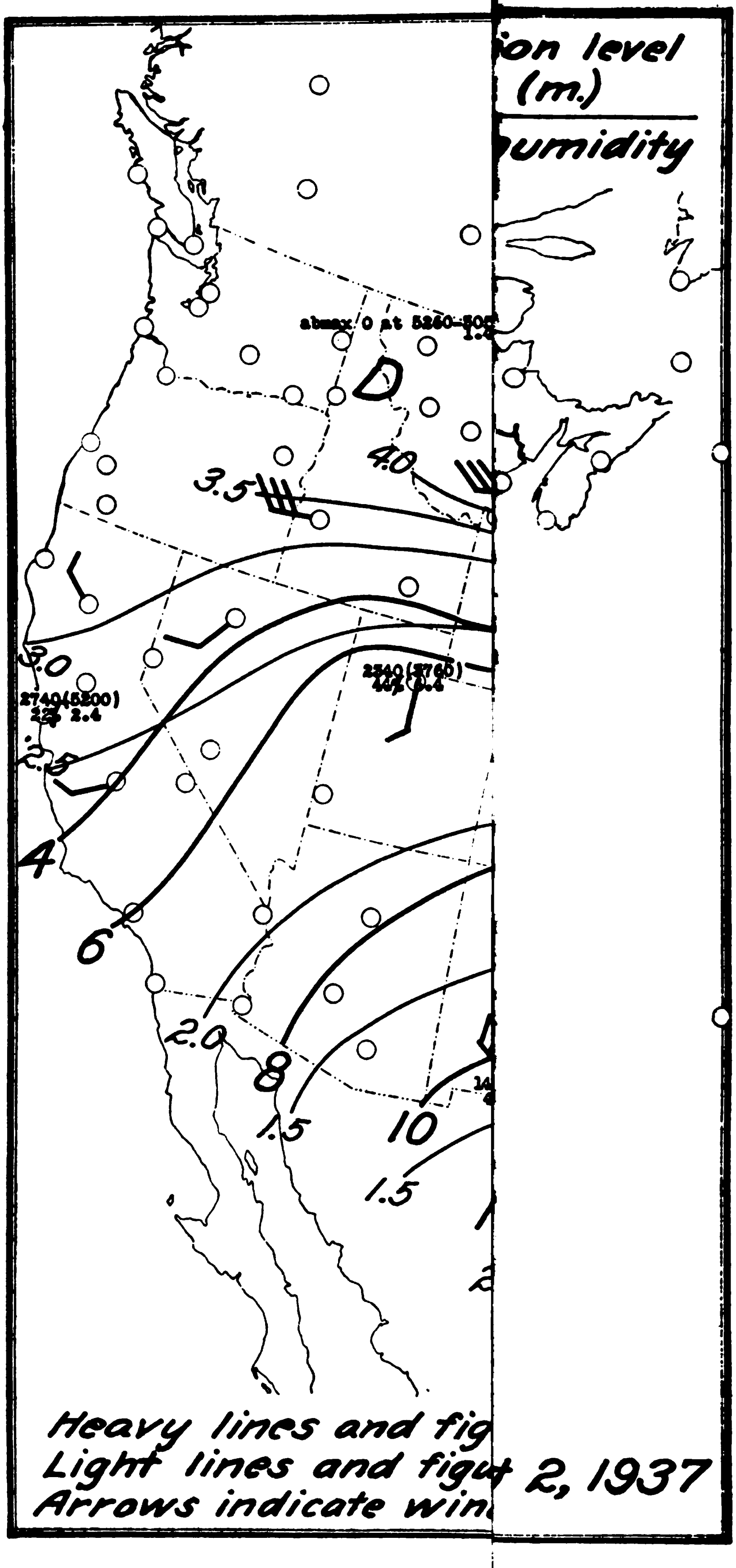
r
t
y
r
e
t
-
d
e
c

e
s

e
e
g.
s.
n

e
f
n
-
-
r
t
d
n
e

MAP A 1


ion level
(m.)
umidity
D
4.0
3.5
3.0
2740(5200)
2.4
2540(3760)
2.5
4
6
2.0
8
1.5
10
1.5
Heavy lines and fig
Light lines and figu
2, 1937
Arrows indicate win

(2) "Potential temperature," θ, is the temperature a mass of air having an initial temperature T and pressure P would have if brought adiabatically to the 1,000-millibar level. It is constant along a dry adiabatic. It is a conservative air mass property as long as the air undergoes adiabatic changes and remains unsaturated. Since the mean motions of the atmosphere are adiabatic, the surfaces of constant potential temperature contain the streamlines of atmospheric movements; that is, the movements of individual particles may be followed on a surface of constant θ. θ is a function of entropy which is a measure of energy. Charts showing surfaces of constant θ are called "isentropic charts."

(3) Study of isentropic charts has led to the determination of the large-scale patterns of air streamlines. On these charts the bodies

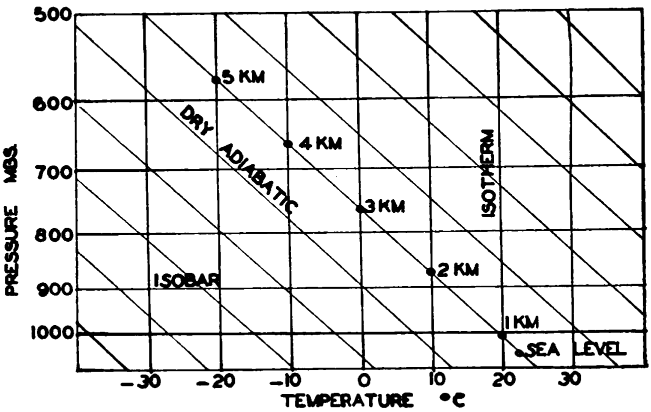


FIGURE 32.—Adiabatic chart.

of moist air are called "moist tongues" and the bodies of dry air are called "dry tongues." These tongues seem to move in a clockwise manner and are continually being dissipated aloft by lateral mixing. This knowledge gives hope for extending the time range of forecasts. Isentropic charts are used for many other purposes and are drawn daily at several Air Corps base weather stations.

c. Saturation adiabatic changes in temperature.—(1) So far we have considered only the vertical displacement of unsaturated particles of air. If the particles rise sufficiently, they will cool to their saturation temperature, the relative himidity will be 100 percent, and condensation will take place. The heat that was originally required to evaporate the water will be released. For each cubic centimeter of water thus condensed, about 600 calories of heat will be set free. This heat is called the "latent heat of vaporization." When the saturated particles rise, they will be heated by the latent heat of vaporization and they will also be cooled due to the expansion of the air as the

pressure decreases. The net result of these two coincident processes is that the saturated air cools at a rate which is about one-half that of the rate of cooling of rising unsaturated air. This resultant rate of cooling is called the "saturation adiabatic lapse rate." It is represented by saturation adiabatics on saturation adiabatic diagrams. There are three synonyms for the term saturation adiabatic; pseudo, moist, and wet adiabatic.

(2) "Equivalent potential temperature," θ_E, is the most conservative of all air mass properties. It is the potential temperature a

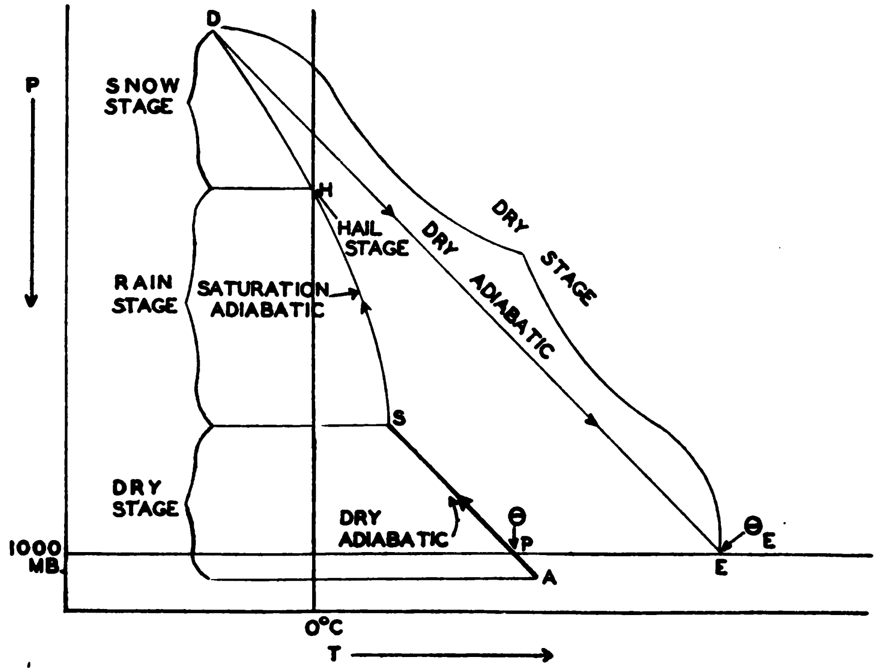


FIGURE 34.—Potential temperature, equivalent potential temperature, and convection stages in the atmosphere.

particle of air would have if lifted until all water vapor is removed. It remains constant both during the saturated and unsaturated stages. It is of great value in identifying air masses, its range in the North American air masses being from 250° A. to 359° A. This 109° spread for nine air masses gives sufficient variation so that each air mass may be put in its own niche. Appreciable changes in equivalent potential temperature are an indication that a new air mass is being formed or encountered.

(3) Figure 34 illustrates the meaning of θ_E with reference to the original particle at A and the changes of state that would occur during the lifting of the air at A until it became absolutely dry. The temperature at P in ° A is θ. If lifted A would remain unsaturated, or in the

dry stage, to *S*, the condensation level. From *S* to *H*, *A* would follow a saturation adiabatic and water would be falling out to form the rain stage. At *H*, any water in liquid form would be frozen to form the hail stage. From *H* to *D* the water vapor would sublimate directly from the gaseous to the solid state to form the snow stage. Assuming the particle to be absolutely dry at *D*, if brought down, it would descend dry adiabatically to *E*. The temperature at *E* in ° *A* is the θ_E of the particle *A*. Note that the θ_E of *A* has not changed during this entire process. Figure 34 also illustrates why there is

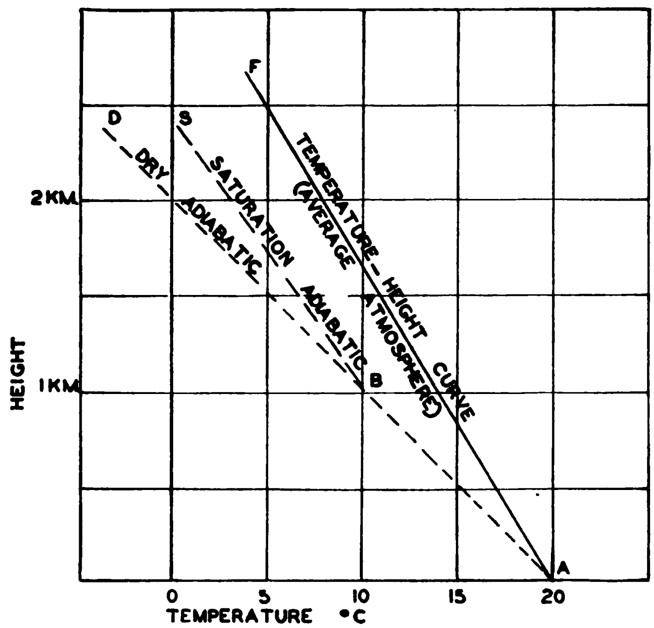


FIGURE 35.—Stable air.

plenty of rainfall on the windward side of high mountains and why the region to the lee is a hot desert.

d. Stability.—A temperature-altitude curve with the same lapse rate as the average lapse rate of the troposphere (6° C./km.) is shown in figure 35. The particle at sea level has a temperature of 20° C., and we assume that this particle will become saturated at 10° C. If this isolated particle is lifted, it will cool adiabatically until its temperature becomes 10° C., which will occur at the 1-kilometer level. From that point on up, the decrease of temperature with altitude will be at the saturation adiabatic lapse rate and the rising particle will move along a saturation adiabatic curve. It is seen that throughout both the dry adiabatic and saturation adiabatic processes, the temperature of the rising particle will always be less than that of the surrounding air. The density of the rising particle will therefore be continuously

greater than that of the surrounding air and if not held to its position or forced up, it would tend to sink to its original level. The same forces would act upon any particle lifted from its original position on the temperature-height curve. Conversely, if any particle along the temperature-height curve were forced down, it would be continuously warmer than the surrounding air and tend to return to its original position. Therefore, since this temperature height curve represents average conditions, the atmosphere is normally stable. Any curve on this figure which shows a less rapid rate of change of temperature with altitude than that of the dry adiabatic represents a layer of air which is stable for the unsaturated state. Such lapse rates are referred to as being less than the dry adiabatic lapse rate. Lapse rates which are less than the saturation adiabatic represent air that is stable for the saturated state. An infinite number of lines could be drawn parallel to the dry adiabatic and they would all be dry adiabatics. A similar number of lines could be drawn to represent saturation adiabatics and they would be roughly parallel to the saturation adiabatics shown but not exactly parallel due to the different amounts of water vapor that it is possible for the air to hold at different temperatures. Also, as altitude increases, the saturation adiabatics approach parallelism to the dry adiabatics because of the continually decreasing amount of water content of the air.

e. Instability.—The temperature-height curve in figure 36 represents unstable air. Assume that the surface particle has a temperature of 20° C. and will become saturated at the 1-kilometer level when the temperature is 10° C. If this particle is lifted, it will follow the dry adiabatic to the 1-kilometer level and then the saturation adiabatic above that point. This particle will everywhere be warmer than the surrounding air and the temperature differential between it and the free air will gradually increase. It will not only tend to rise because it is less dense than the surrounding air, but its rate of ascent will be accelerated. The same features will hold true for any particle that is lifted from its original position. Conversely, any particle that is given an impetus downward will continually grow more dense than the surrounding air and will be accelerated downward. These same features will hold true for any temperature altitude curve along which the rate of change of temperature with altitude is greater than that along a dry adiabatic. These lapse rates are referred to as being greater than the dry adiabatic. They are frequently called "superadiabatic." All such curves represent layers of air that are unstable for the unsaturated state. All lapse rates which are greater than the

saturation adiabatic represent air that is unstable for the saturated state.

f. Neutral equilibrium.—With dry air, this state is reached when the lapse rate is equal to the dry adiabatic. Under this condition, the rising particle will possess the temperature of the surrounding air at every stage in its ascent. Thus it will neither assist nor resist replacement. If the rising air is saturated, the conditions for neutral equilibrium require that the lapse rate equal the saturation adiabatic.

g. Conditional instability.—(1) Since the rate of cooling of a rising saturated mass is less than that for a dry one, there frequently exists in the atmosphere a lapse rate which is unstable for the saturated

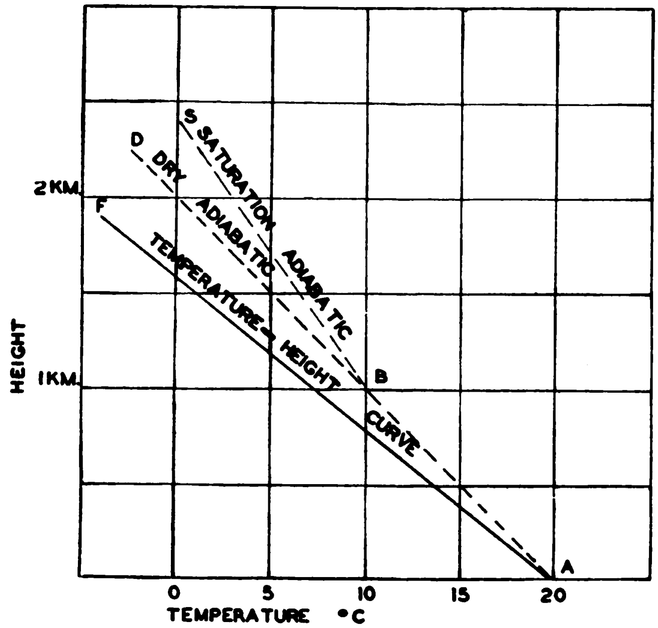


FIGURE 36.—Unstable air.

state, but stable for the unsaturated one. If, for example, the observed temperature lapse rate in the atmosphere is less than the dry adiabatic but greater than the saturation adiabatic, and a particle is forced to some point above the condensation level, it will begin to find itself warmer than its surroundings as it moves along its saturation adiabatic curve. Such a thermal state in the atmosphere is termed "conditional instability." This simply means that the air is potentially unstable, and if mechanical forces be applied to lift it above the saturation level, the instability will be realized. These forces may be caused by terrain features or frontal activity. Conditional instability is illustrated in figure 37.

(2) If the surface particle of air is forced aloft, it will move along the dry adiabatic to its condensation level *C* which is assumed to be

at a temperature of 10° C. and an elevation of 1 kilometer. From *C* it will follow a saturation adiabatic curve characterized by an increase of slope with elevation. Along the curve *SCL* the rising particle was colder than its surroundings and some mechanical means of lifting it to the level *L* was necessary. At *L* it was at the same temperature as the surrounding air. Along the portion of the saturation adiabatic represented by the curve *LBP*, it was continuously warmer than the surrounding air, went up of its own accord without help from any outside source, and was accelerated by the forces produced by this thermal instability. Therefore *L* represents the level of free con-

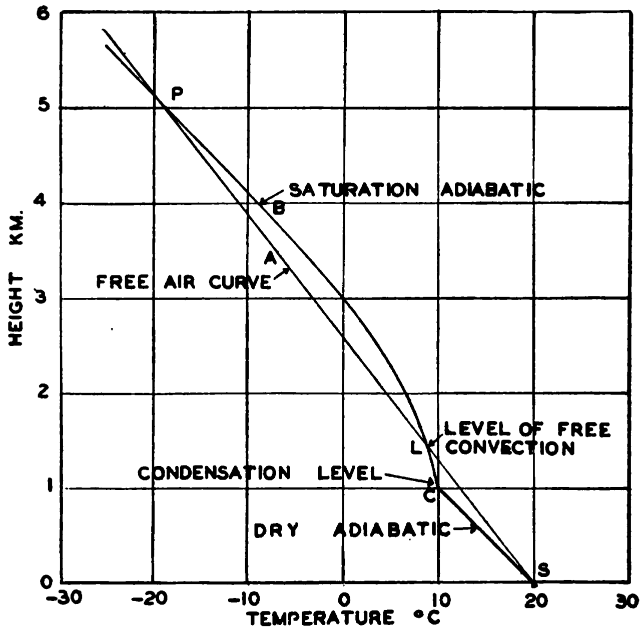


FIGURE 37.—Conditional instability in the atmosphere.

vection. At *B* the difference between the density of the rising air and its surroundings is at a maximum and therefore its acceleration reaches its greatest value. Above *B* the slope of the saturation adiabatic is greater than the slope of the curve representing the temperature lapse rate of the surrounding atmosphere. Therefore, above *B*, the acceleration of the rising particle will decrease. The vertical acceleration becomes zero at *P* where the particle again reaches the temperature of its surroundings. Although the acceleration is decreasing, the value of the acceleration is still positive between *B* and *P* and its vertical velocity continues to increase, reaching its maximum value at *P*. Its momentum will carry it beyond *P* and thus develop negative accelerations which tend to damp out the vertical motion, because above *P* the particle is colder than its surroundings.

(3) Figure 37 shows conditional instability for displacements of an isolated portion of the atmosphere relative to its surroundings. This is an excellent illustration of what occurs in a thunderstorm, which may be considered to be a vertical displacement of an isolated portion of the atmosphere. *P* represents the level at which maximum vertical velocities are obtained. This occurs at 4 kilometers or approximately 13,000 feet. In the lower levels of the thunderstorm, even above the condensation level, or between *C* and *L*, where a mechanical force is still necessary to produce any upward motion, the upward velocities must be relatively small. In some cases, appreciable upward velocities are developed even below the base of the thunderstorm cloud due to a state of instability in the unsaturated portion of the atmosphere below the base of the cloud. Nevertheless, in the higher levels of the cloud where large accelerations are being produced, the upward velocities attain their maximum values. The velocity gradients produced may be sufficient to cause structural failure. Therefore, it is always advisable to avoid thunderstorms if possible. For the reasons given above, and from other considerations, it seems advisable, when required, to fly through a thunderstorm at altitudes of about 1,500 feet above the ground.

(4) A thunderstorm is not necessarily the result of a superadiabatic lapse rate in the atmosphere. Usually the only part that a superadiabatic lapse rate plays in the development of a thunderstorm is in starting vertical motions below the condensation level. Superadiabatic lapse rates are usually confined to the layer near the surface of the earth where they have been produced by diurnal heating. All air mass thunderstorms take place in air characterized by conditional instability.

(5) The air masses frequenting the United States which have attained their physical characteristics over the Gulf of Mexico, the Caribbean Sea, and the tropical Atlantic Ocean, Tg and Ta air, are characterized by conditional instability and are the masses in which the occurrence of local thunderstorms is observed to be most frequent.

h. Vertical displacement of layers of air.—The curve joining the points of an upper air sounding is called the "characteristic curve" for the air column. By testing the particles of air at the inflection points of this curve for stability, it is possible to determine the stability of the different layers of air. The stability of particles of air with respect to their surroundings is important in shower and thunderstorm formation. However in the more important and larger scale, vertical displacements of air such as the movement of a widespread tropical air mass over a wedge of polar air or a mountain range, the stability

213541°—40——5

of layers of air becomes paramount. The effects of lift and subsidence on layers of stable and unstable air are summarized in table VI. Layers of air that are in neutral equilibrium do not change their type of stability as long as they remain either in the unsaturated or saturated state. A layer of unsaturated air that is in neutral equilibrium frequently becomes unstable if lifted until it becomes saturated. Fog and very low clouds occur in very stable layers of air. Thunderstorms, hail, and heavy rain occur in very unstable layers of air.

TABLE VI.—*Effect of lift and subsidence on stability of layers of air*

	Unsaturated layer		Saturated layer	
	Stable	Unstable	Stable	Unstable
Lift	Less stable	Less unstable	Less stable	More unstable.
Subsidence	More stable	More unstable	do	Less unstable.

i. Thermodynamical diagrams.—Two types of thermodynamical diagrams are the adiabatic chart and the saturation adiabatic chart. Other thermodynamical diagrams are the tephigram, the Hertz-Neuhoff diagram, the Refsdal diagram, the Rossby diagram and the Clark diagram. The tephigram and the Rossby diagram are standard Air Corps diagrams. The upper air temperature, pressure, and humidity data that are received daily are plotted on these diagrams. Study of the resultant curves makes it possible for the forecaster to gain accurate information concerning the existing meteorological conditions aloft. Half the task of the forecaster is to be able to explain past and existing weather. Without this knowledge, any forecasts that he may make will be without a firm foundation. The chief specific uses of thermodynamical diagrams are to—

(1) Identify air masses.

(2) Determine the stability of isolated particles of air.

(3) Determine the stability of layers of air.

(4) Identify overrunning air masses.

(5) Forecast the time of formation and dissipation of fog and low clouds.

(6) Forecast the elevation of the base and top of clouds.

j. Upper air soundings.—Temperature, pressure, and humidity data have been obtained aloft by various means.

(1) Kites with recording instruments attached supplied a large portion of the early data.

(2) Free balloons with attached instruments have furnished data up to 130,000 feet. Manned balloons used in stratosphere flights have gone to 72,000 feet. Data obtained from these sources have been useful for research but not in forecasting due to the delay required in obtaining the data and the infrequency of flights.

(3) Captive balloons are useful for obtaining data in the lower levels.

(4) For making airplane observations, a meteorograph containing pressure, temperature, and humidity elements attached to an airplane has been used successfully. This method is limited by the

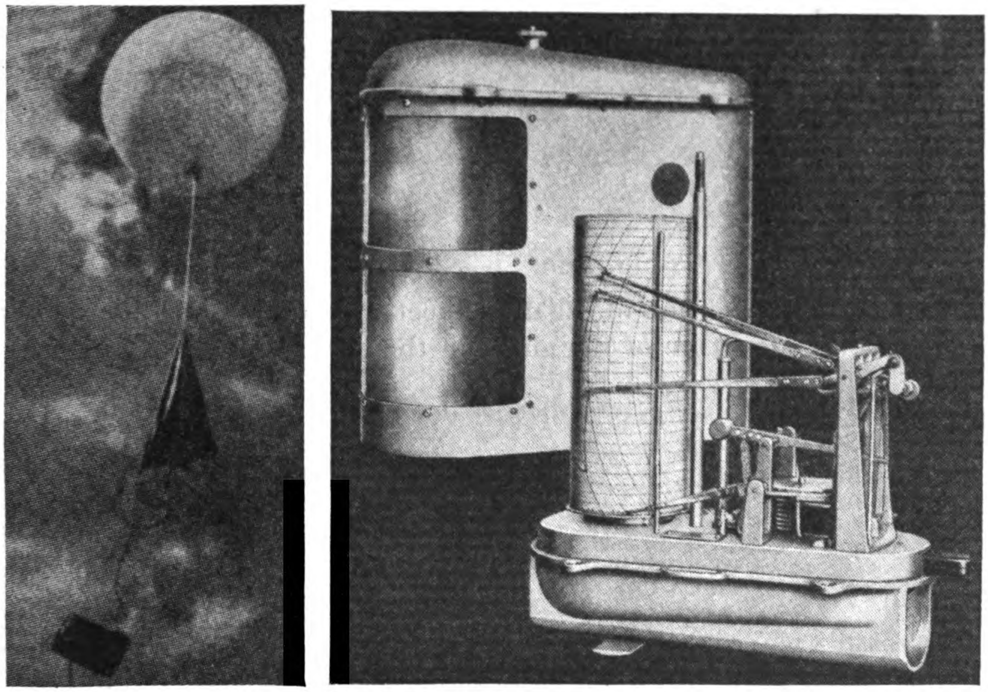


FIGURE 38.—Airplane meteorograph.

ceiling of the airplane, adverse weather, and the time required for ascent and descent.

(5) The radiometeorograph contains the same elements as an airplane meteorograph, plus a radio transmitter. This instrument weighs less than 2 pounds, is attached to a free balloon, rises until the balloon bursts, then is let down by a parachute. The data are transmitted automatically during the ascent and descent. This method may be used in all weather except thunderstorms. It obtains data to great heights, may be used at varied locations, and, most important, the data are immediately available.

(6) Rocket flights offer the possibility of obtaining data from very high levels.

(7) The aerographic data sheet is used for rapid determination of air structure. A thorough knowledge of thermodynamical diagrams

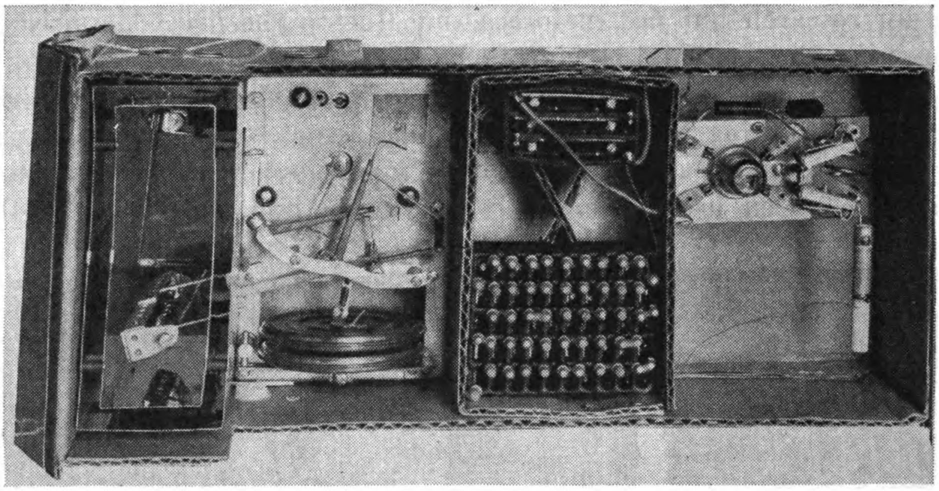


FIGURE 39.—Radiometeorograph.

is essential for proper use of the data sheet. A well-trained forecaster can "see" the structure of the air from the aerographic data sheet.

Aerographic Data Sheet

Time sounding: 0400ES.
Computed by: A. J. R.

Station: Oklahoma City.
Date: May 6, 1939.
Air mass: Tg/RPc.

Elev. (DCM.)	Pres. (MB.)	Temp. (°C.)	R. H. (%)	Θe (°A.)	W g/kg.	Lift (M.)	dΘe dz/km	Clouds	Air mass	Remarks
40	965	17	60	313	7. 4	1, 000	+32	Clear	${}_4R_{p_{c_4}}$	Inversion overrunning potentially unstable.
80	923	20	60	326	9. 5	1, 000	−3		T_g	Almost isothermal.
170	824	12	69	323	7. 6	600	+20			
190	809	13	69	327	8. 3	600	−10			Neutral equilibrium for saturated state.
210	786	11	70	325	7. 4	600	0			
230	766	12	53	325	6. 0	1, 100	0			Low lift. Stable.
330	684	5	66	325	5. 2	700	−2			
390	629	−1	79	324	4. 6	300	0			
550	519	−10	52	324	1. 8	900	+0. 6			
720	412	−24	54	325	. 8	600	+2. 5			
920	309	−40	49	329	. 2	400				
1110	232	−54								
1470	133	−56								
1890	68	−62							Elev. (feet)	Pres. (inches)
									5, 000	24. 96
									10, 000	20. 78
									14, 000	17. 78

SECTION V

CLOUDS

36. General.—Clouds are the most important single element visible to the aviator. Their proper interpretation should be a constant goal of all who fly aircraft. The knowledge of clouds is acquired only after having studied cloud photographs and examined the sky. It requires long practice and all aerial navigators must possess this knowledge.

37. Composition.—*a*. When a volume of air saturated with water vapor is cooled, it condenses in either the liquid or solid form, depending upon whether the temperature is above or below 0° C. This condensation does not occur throughout the entire mass of humid air, but around small condensation nuclei, chiefly sea salts, which are constantly present in the atmosphere. A cloud then is composed of a great number of small water droplets, ice crystals, or both, which are separated from each other but yet limit the visibility. The diameter of the water droplets is very small, ranging from 1 to 70 microns with the most frequent diameter being 12 microns. There are about 50 to 500 of these particles in a cubic centimeter of cloudy air. The rate of fall of these droplets is so small, a few millimeters per second, that the slightest ascending air current is sufficient to hold them aloft. Rain drops, on the contrary, which are composed of an accumulation of small droplets, are comparatively large and fall with appreciable velocities.

b. Although very numerous, the droplets which constitute a cloud are so small that they represent only a few grams of water per cubic meter; they exist in cloudy air in which the amount of water in the vapor state far exceeds that in the liquid state. The relative humidity in the midst of a cloud is always slightly less than 100 percent, because it is exactly 100 percent only in the immediate vicinity of the droplets with a less value in the intermediate spaces. Relative humidities as

low as 50 percent have been measured in clouds. Beginning at low altitude, the relative humidity decreases with height to have a value at 10 kilometers similar to the surface value in the middle of the Sahara Desert. It is rare then in the middle latitudes to encounter clouds above 10 kilometers. At high altitudes where the temperature is constantly less than 0° C., it is possible for clouds composed only of ice crystals to form. The cooling of moist air which leads to the condensation of the water vapor that it contains is most frequently caused by vertical motions which carry the air to higher altitudes. Conversely, subsiding air is heated by compression and if it contains condensed water (cloudy air), it will become clear.

38. Classification.—*a*. Clouds are classified according to form and appearance, but consideration is also given to the physical processes producing them. There is a general relation between the forms of clouds and their heights as shown by actual measurements. The temperature, moisture, and movements of the air differ characteristically at the various levels above the earth's surface and hence there are significant differences in the formation of clouds as well as the apparent effects of distance or height above the observer.

b. In the International System there are ten genera, and in addition, certain species, varieties, and special features. About 75 different types of cloud and sky are internationally recognized. A student of clouds, as each pilot should be, would find it valuable to make a detailed study of all these types. Only by such a study will he be able to see and understand most of the visible weather signs. The ten genera and their heights, as given in the International Cloud Atlas, are shown in table VII. The mean heights are for temperate latitudes and refer not to sea level but to the general land level in that region. There is nearly always some variation from the mean height which serves merely as a guide to the general elevation. In certain cases there may be large departures from the mean height. Pilots who have access to the International Cloud Atlas should study the illustrations, diagrams, and comments contained therein.

TABLE VII.—*Classification of clouds*

Family	Mean heights (feet)	Stratiform clouds	Cumuliform clouds
High clouds	Top, 40,000 Base, 20,000	Cirrus (I) Cirrostratus (I)	Cirrocumulus (I).
Middle clouds	Top, 20,000 Base, 6,500	Altostratus (I) Nimbostratus (I)	Altocumulus (I+W)
Low clouds	Top, 6,500 Base, near surface.	Stratocumulus (W) Stratus (W)	Stratocumulus (W).
Clouds with vertical development.	Top, cirrus level. Base, 1,600		Cumulus (W). Cumulonimbus (I+W)

c. Cirrus clouds may be observed as low as 10,000 feet in temperate regions and at lower levels in higher latitudes. In the polar regions and in extremely cold weather elsewhere, ice spicules are occasionally observed in the air at or near the surface. Clouds composed at least partially of water droplets can exist at very low temperatures; sometimes low clouds are composed of a mixture of water droplets and ice crystals or snow.

d. Two additional methods of classification have been added.

(1) The first divides the clouds on the basis of stability into cumuliform and stratiform clouds.

(*a*) *Cumuliform clouds* are heaped and form as the result of instability in the atmosphere. The air within them is rough. The surrounding air may be either rough or smooth depending upon whether they are imbedded in an unstable layer or column of air or not. When in an unstable layer or column of air, their vertical growth is revealed by form and movement. When in a stable layer, their vertical growth is being suppressed.

(*b*) *Stratiform clouds* are flat, occur in layers, and form in stable air. The air within and surrounding them is smooth.

(2) The second method shows whether the clouds consist of water droplets, ice crystals, or both. This differentiation is shown in the table by an "I" for ice clouds, a "W" for water clouds, and "I+W" for clouds that contain both ice and water.

e. Clouds may change in the course of development or dissipation from one type to another. The number of possible variations of types is infinite.

f. Nimbostratus has been grouped with the middle clouds in accordance with its latest definition as an ice cloud.

39. Types and descriptions.—*a. Cirrus.*—(1) Cirrus clouds are detached clouds of delicate and fibrous appearance, generally white in color, often of a silky appearance.

(2) Cirrus appears in the most varied forms, such as isolated tufts, lines drawn across a blue sky, branching featherlike plumes, and curved lines ending in tufts. They are often arranged in bands which, owing to the effect of perspective, converge to a point on the horizon.

(3) Cirrus clouds are always composed of ice crystals, and their transparent character depends upon the degree of separation of the crystals. As a rule, when these clouds cross the sun's disk, they hardly diminish its brightness. But when they are exceptionally thick they may veil its light and obliterate its contour.

(4) Sometimes isolated wisps of snow are seen against the blue sky and resemble cirrus; they are less pure white and less silky than

cirrus; wisps of rain are definitely gray, and a rainbow, should one be visible, shows their nature at once, for this cannot be produced in cirrus. (See figs. 60, 61, 63, 64, and 72.)

(5) Before sunrise and after sunset, cirrus is often colored bright yellow or red. These clouds are lit up long before other clouds and fade out much later.

b. Cirrocumulus.—(1) Cirrocumulus is a cirriform layer or patch composed of small white flakes or of very small globular masses, usually without shadows, which are arranged in groups or lines or more often in ripples resembling those of sand on the seashore. (See fig. 62.)

(2) In general, cirrocumulus represents a degraded state of cirrus and cirrostratus, both of which may change into it. This is an ice cloud. Real cirrocumulus is uncommon.

c. Cirrostratus.—(1) Cirrostratus is a thin, whitish veil which does not blur the outlines of the sun or moon, but usually gives rise to halos. Sometimes it is quite diffuse and merely gives the sky a milky look; sometimes it more or less distinctly shows a fibrous structure of disordered filaments. (See figs. 63 and 64.)

(2) Cirrostratus is an ice cloud. A sheet of cirrostratus which is very extensive, though it may be interrupted by rifts, nearly always ends by covering the whole sky. The border of the sheet may be straightedged and clear-cut but more often it is ragged or cut up. The sheet is never thick enough to prevent shadows of objects on the ground.

d. Altocumulus.—(1) Altocumulus is a layer (or patches) composed of laminae or rather flattened globular masses, the smallest elements of the regularly arranged layer being fairly small and thin and with or without shading. These elements are arranged in groups, in lines, or in waves, following one or two directions, and are sometimes so close together that their edges join. (See figs. 57, 58, 59, and 63.)

(2) The limits within which altocumulus is met are very wide. At the greatest heights, altocumulus made up of small elements resembles cirrocumulus; altocumulus, however, is distinguished by not possessing any of the following characters of cirrocumulus:

(*a*) Connection with cirrus or cirrostratus.

(*b*) An evolution from cirrus or cirrostratus.

(*c*) Properties due to physical structure (ice crystals).

(3) Altocumulus clouds often appear at different levels at the same time. They are often associated with other types of clouds. The air is often hazy below altocumulus clouds. When the elements of a

sheet of altocumulus fuze together and make a continuous layer, altostratus or nimbostratus is the result. A sheet of altostratus can change into altocumulus. It is interesting to note that one may often observe descending trails of snow or rain to which the name "virga" has been given.

(4) Altocumulus with scattered cumuliform tufts occurs in two important varieties:

(*a*) *Altocumulus floccus.*—These are tufts resembling small cumulus clouds without a base and more or less ragged, or high flaky cumulus clouds often with trailers of snow or rain. They indicate overrunning unstable air.

(*b*) *Altocumulus castellatus.*—These are cumuliform masses with more or less vertical development, arranged in a line, and resting on a commonly horizontal base. They indicate a high degree of instability aloft in the overrunning air. They often precede showers or thunderstorms. Overrunning Tg, particularly in the western United States, occurs typically with this cloud form.

e. Altostratus.—(1) Altostratus is striated or fibrous veil more or less gray or bluish in color. This cloud is like thick cirrostratus but without halo phenomena; the sun or moon shows vaguely. Sometimes it is very thick and dark, completely hiding the sun or moon. Rain or snow may fall from altostratus, but when the rain is heavy, the cloud layer becomes thicker and lower, forming nimbostratus.

(2) A sheet of low altostratus may be distinguished from a somewhat similar sheet of nimbostratus by the following characters: Nimbostratus is of a much darker and more uniform gray and shows no whitish gleam or fibrous structure. Thickening altostratus is usually followed by steady and persistent precipitation. (See figs. 55, 56, and 59.)

f. Stratocumulus.—(1) This is a layer (or patches) composed of globular masses or rolls; the smallest of the regularly arranged elements are fairly large; they are soft and gray, with darker parts. These elements are arranged in groups, in lines, or in waves, alined in one or two directions. Very often the rolls are so close that their edges join; when they cover the whole sky, they have a wavy appearance. (See figs. 49, 50, 59, 73, and 79.)

(2) Stratocumulus has definite shadows. The cloud is called nimbostratus when the cloud elements of stratocumulus have completely disappeared and when, owing to falling trails of precipitation, the lower surface no longer has a clear-cut boundary. Stratocumulus can change into stratus and vice versa.

g. Stratus.—(1) Stratus is a low uniform layer of cloud resembling fog but not resting on the ground. When this very low layer is broken up into irregular shreds, it is called fractostratus.

(2) A veil of true stratus generally gives the sky a hazy appearance which is very characteristic but which may cause confusion with nimbostratus. When there is precipitation, the difference is manifest; nimbostratus gives continuous rain (sometimes snow) precipitation composed of drops which may be small and sparse or else large and close together, while stratus only gives "drizzle"; that is, small drops very close together. The lower surface of nimbostratus always has a wet appearance with widespread trailing precipitation, called virga; it is quite uniform and it is not possible to make out definite detail; stratus on the other hand has a drier appearance and, however uniform it may be, it shows some contrast and some lighter transparent parts. (See figs. 51, 52, 59, 63, 65, and 74.)

(3) Stratus is often a local cloud and when it breaks up the blue sky is seen. Fractostratus sometimes originates from the breaking up of a layer of stratus; sometimes it forms independently and develops till it forms a layer below altostratus or nimbostratus, which latter may be seen in the interstices.

h. Nimbostratus.—(1) Nimbostratus is a thick, amorphous, and rainy layer of a dark gray color, usually nearly uniform; feebly illuminated seemingly from inside. Precipitation is in the form of continuous rain or snow. Often there is precipitation that does not reach the ground; then the base of the cloud looks wet because of general trailing virga so that it is not possible to determine the limit of its lower surface. (See fig. 53.)

(2) The usual evolution is as follows: A layer of altostratus grows thicker and lower until it becomes a layer of nimbostratus. Beneath the latter there is generally a progressive development of very low ragged clouds, isolated at first, then fuzing together into an almost continuous layer. These very low clouds are called fractocumulus or fractostratus according to whether they appear more or less cumuliform or stratiform. Generally the rain falls after the formation of these very low clouds, which are then hidden by the precipitation or may even melt away under its action. The vertical visibility then becomes very poor. In certain cases the precipitation may precede the formation of fractocumulus of fractostratus, or it may happen that these clouds do not form at all. These low clouds are sometimes called "scud." Ceilings and visibilities associated with nimbostratus are usually low.

i. Cumulus.—(1) Cumulus clouds are dense clouds with vertical development; the upper surface is dome-shaped and exhibits rounded protuberances, while the base is nearly horizontal.

(2) When the cloud is opposite the sun, the surfaces normal to the observer are brighter than the edges of the protuberances. When the light comes from the side, the clouds exhibit strong contrasts of light and shade; on the other hand, against the sun, they look dark with a bright edge. (See figs. 43, 44, 45, 46, 67, 75, 76, 77, 80, 81, and 82.)

(3) True cumulus is definitely limited above and below and its surface often appears hard and clear-cut. A cloud resembling ragged cumulus in which the different parts show constant change is designated "fractocumulus."

(4) Typical cumulus over land develops on days of clear skies and is due to the currents of diurnal convection; it appears in the morning, grows, and then more or less dissolves again toward the evening. Cumulus, whose base is generally of a gray color, has a uniform structure; that is, it is composed of rounded parts right up to its summit with no fibrous structure. Even when highly developed, cumulus can only produce light precipitation.

(5) When cumulus reaches the altocumulus level, it is sometimes capped with a light, diffuse, and white veil of more or less lenticular shape, with a delicate striated or flaky structure on its edges; it is generally shaped like a bow which may cover several domes of the cumulus, and finally be pierced by them. This cloud which does not constitute a species is given the name of "pileus," meaning a cap or hood.

(6) Cumulus is the most common type of cloud and is a good indicator of the trend of the weather. When the cumuli are growing, the weather is generally getting worse. Growing cumuli in the evening or at night is almost a sure sign of increased weather activity. When the cumuli are dissipating, the weather is improving. Two important species that indicate these trends are as follows:

(*a*) *Cumulus humulis.*—Fair-weather cumulus. Cumulus with little vertical development and flat bottoms. These clouds are generally seen in fine weather. Their upward extent is limited by a layer of stable air. They result from surface convections which penetrate the stable layer. They are embedded in the stable air and project weak shadows. This is a water cloud.

(*b*) *Cumulus congestus.*—Swelling, bulging cumulus with domes having a cauliflower appearance. Towering portions rapidly build up from the flat base. The cloud surface appears hard and well-defined. They often develop into cumulonimbus. The following rain is of the

showery type. These clouds precede thunderstorms and are water clouds.

j. Cumulonimbus.—(1) These are heavy masses of cloud, with great vertical development, whose cumuliform summits rise in the form of mountains or towers, the upper parts having a fibrous texture and often spreading out in the shape of an anvil. (See figs. 47, 48, 61, and 66.)

(2) The base resembles nimbostratus, and one generally notices virga. This base often has a layer of very low ragged clouds below it (fractostratus, fractocumulus). Cumulonimbus clouds generally produce showers of rain or snow and sometimes hail, and often thunderstorms as well. If the whole of the cloud cannot be seen, the fall of a real shower is enough to characterize the cloud as a cumulonimbus.

(3) Although the upper cirriform parts of a cumulonimbus may take on varied shapes, in certain cases they spread out into the form of an anvil. To this formation the name "incus" is given.

(4) In certain types of cumulonimbus, especially common in spring in moderately high latitudes, the fibrous structure extends to nearly the whole cloud mass, so that the cumuliform parts almost disappear; the cloud is reduced to a mass of cirrus and of virga. Pileus is seen with cumulonimbus clouds as with cumulus.

(5) When a cumulonimbus covers nearly all the sky, the base alone is visible and resembles nimbostratus, with or without fractostratus or fractocumulus below. The difference between the base of a cumulonimbus and nimbostratus is often rather difficult to make out. If the cloud mass does not cover all the sky, and if only small portions of the upper parts of the cumulonimbus appear the difference is evident; if not, it can only be made out if the preceding evolution of the clouds has been followed or if precipitation occurs; its character is violent and intermittent showers occur as opposed to the relatively gentle and continuous precipitation of a nimbostratus.

(6) The front of a thunder cloud of great extent is sometimes accompanied by a roll cloud of a dark color in the shape of an arch, of a frayed out appearance, and circumscribing a part of the sky of a lighter gray. This cloud is named "arcus" and is nothing more or less than a particular case of fractocumulus or fractostratus.

(7) Fairly often a mammatus structure appears in cumulonimbus, either at the base or on the lower surface of the lateral parts of the anvil. "Mammatus" is the term applied to clouds whose lower surfaces form pouches or breasts. When a menacing cloud covers the sky and virga and mammatus structures are both seen, it is a sure sign that the cloud is the base of a cumulonimbus even in the absence of all other signs.

(8) Cumulonimbus is a real factory of clouds; it is responsible in great measure for the clouds in the rear of disturbances. By the spreading out of the more or less high parts and the melting away of the underlying parts, cumulonimbus can produce more or less thick sheets of altocumulus or stratocumulus (spreading out of the cumuliform parts) and dense cirrus (cirrus nothus).

(9) Among the principal species of cumulonimbus may be noted—

(a) *Cumulonimbus calvus.*—Calvus means "bald." Cumulonimbus calvus is cumulonimbus characterized by the thunderstorm or the shower that it causes or by virga, but in which no cirriform parts can be made out. Nevertheless the freezing of the upper parts has already begun; the tops are beginning to lose their cumulus structure, that is their rounded outlines and clear-cut contours; the hard and "cauliflower" swellings soon become confused and melt away so that nothing can be seen in the white mass but more or less vertical fibers. The freezing, accompanied by the change into a fibrous structure, often goes on very rapidly.

(b) *Cumulonimbus capillatus.*—Cumulonimbus which displays distinct cirriform parts, having sometimes but not always, the shape of an anvil. This is the characteristic cloud of the thunderstorm. It is composed of a mixture of ice crystals and water droplets. An anvil is formed when the summit of the cloud spreads out under a very stable layer or an inversion. The anvil is usually cirriform in character and may be penetrated by bulging cumulus that goes on up to form another anvil at a higher level and leave a cirriform ring or "skirt" about the cloud at a lower level.

(10) The principal varieties of cumulonimbus are—

(a) *Lenticularis.*—Clouds of an ovoid shape, with clean-cut edges and sometimes irisations, especially common on days of strong, dry winds in rough country. This form exists at all levels from cirrostratus to stratus.

(b) *Mammatus.*—Clouds whose lower surfaces form pouches or breasts.

(c) *Undulatus.*—Clouds composed of elongated and parallel elements, like waves of the sea. There is sometimes an appearance of two distinct systems, as when the cloud is divided into rounded masses by undulations in two directions.

(d) *Radiatus.*—Clouds in parallel bands, which owing to perspective, seem to converge to a point on the horizon or to two distant points if the bands cross the whole sky.

k. Fog.—Fog is a cloud that touches the ground. In flat areas it is usually a stratus cloud that rests on the ground. In rough

country, the higher ground may be covered by either stratiform or cumuliform clouds to form fog. Fog is discussed in detail in section X.

40. Clouds as seen in flight.—The clouds as seen by terrestrial observers are as described in paragraph 39. The pilot sees them similarly while flying below them. However, he frequently flies above or in some of the types given and then they appear differently. The essential differences in structure of the clouds which have appeared to a terrestrial observer are modified for the pilot and allow the classification to be simplified according to his point of view. He may recognize readily the following groups:

a. High clouds.—Cirrus and cirrostratus, which are not commonly reached by aviators. Their appearance remains the same as from the ground.

b. Clouds of the altostratus type.—Often very thick, but not very opaque. The sun generally appears shortly after they are entered.

c. Clouds in a layer or forming a horizontal cover.—A very large group, comprised of the following formations as seen from the ground: stratus, stratocumulus, and altocumulus, which, when observed from above, present a very similar appearance. The upper surface has a characteristic furrowed appearance like a sea of clouds. The shadow of an airplane flying over them is frequently surrounded by one or two orders of spectral colors.

d. Haze.—Normally present in the lower air layers. It is the light reflected from the upper surface of the haze which obscures the ground when looking down on the side of the sun. If the observer turns away from the sun, the visibility toward the ground improves. The top of the haze is often sharply defined, below which the air appears gray or murky and above which it appears very clear. The air is usually smooth above the haze and rough in the hazy layer. Sometimes several haze lines appear when there is a series of small inversions.

e. Convection clouds.—Cumulus and cumulonimbus. Near the horizon, cumulus clouds can, because of the effect of perspective give the appearance of a continuous layer with irregular summits. Sometimes the tops of cumulus clouds pierce a higher cloud layer. The tops of the large cumulonimbus clouds, of which the base is hidden, may sometimes be seen at distances of more than 200 miles and at altitudes of more than 35,000 feet.

41. Amount and direction of motion.—*a.* The total cloudiness is the fraction of the sky occupied by all the visible clouds. It is determined by estimation and is expressed in tenths (a solid overcast is indicated by 10, a clear sky by 0), or sometimes in quarters.

b. The direction of motion of clouds often may be easily observed by sighting on a steeple, tower, pole, or other structure in an open place. The direction of motion of cloud shadows on the ground may be observed from the air. The speed of the clouds is added in some reports.

42. Visibility.—*a.* The visibility is the maximum distance at which ordinary natural objects may be distinguished. It is measured horizontally at the ground, but the pilot needs to see ahead, above, and below. These visibilities are not the same as the visibility measured at the ground; however, surface visibility is a good indicator in all cases.

b. It is frequently possible to appreciate from the ground oblique visibility, when landmarks on mountains are observed, or vertical visibility by noting the time required for a rising balloon to disappear. These do not give the visibility of the aviator because they are seen from below to above and not from above to below. These visibilities can be different since the lighting and the background is not the same in the two cases. However, all these visibilities usually vary in the same sense, so that when the meteorological visilibity is given, it is very useful to aviators.

c. Visibility may be limited by fog, haze, dust, and precipitation, especially heavy rain and heavy snow.

43. Ceiling.—*a.* When the clouds form a widespread layer, they constitute an obstacle, the ceiling, which limits the altitude to which the pilot may fly without losing sight of the ground. When the pilot flies above the ceiling, he loses sight of the ground, sometimes for several hours; it is then necessary to direct his course by celestial navigation or by the use of radio aids, since it is impossible to measure drift.

b. If it is necessary to let down through the cloud layer or if clouds are encountered that are too high to be flown over, a period of instrument flying is required. Moreover, there is the risk of hitting the ground before coming out of the clouds. The ceiling may have lowered and it has been shown that it is not advisable to put blind confidence in the altimeter. Furthermore, the region may be mountainous. When the cloud layer is not absolutely continuous, if there are holes, it is possible from time to time to see the ground and to use the holes to descend below the ceiling.

c. In spite of the progress of the methods in navigation and in instrument flying, the height of the ceiling remains one of the fundamental pieces of information which the aviator demands. The ceiling is measured during the day by determining the amount of time required for a ceiling balloon with a known ascensional rate to disappear

in the clouds. At night, a projector with a vertical beam is used to make a bright spot on the base of the cloud. This spot is observed through a clinometer by an observer at the opposite end of a base line of known length from the projector as shown in figure 40. The height of the ceiling may be determined by trigonometry after the angle to the spot has been determined. In mountainous regions, measuring the ceiling is simplified during the day by noting the relation of the base of the clouds to known landmarks whose height above the station has previously been determined.

d. Since means have been found to fly in the clouds and to fly above them, the aviator requires more information than simply the height of the ceiling. He should know the altitude, the extent, and the thickness of the different layers of clouds; in sum, a vertical section of the

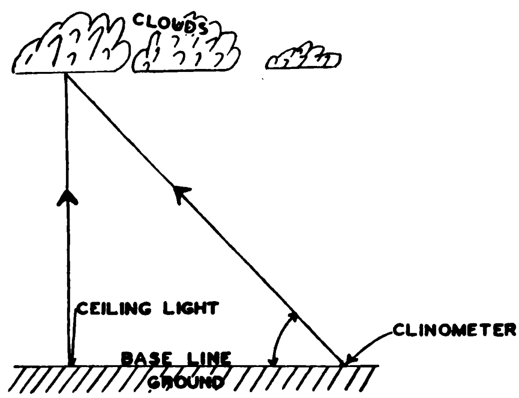


FIGURE 40.—Measurement of the ceiling.

atmosphere in the direction of flight during the day as well as the night. It is possible to see that the pilot will hesitate to penetrate a layer of clouds, especially at night, if he does not know what the ceiling is going to be farther on.

e. The direct information that the forecaster is able to procure concerning the free air conditions above the cloud level implies an upper air sounding, a sounding from which it is possible to use the results immediately (radio meteorograph, captive balloon), and reports from pilots who have observed conditions in the upper air. Lacking soundings and pilot reports, the knowledge recently acquired by the forecasters on the structure of cyclones and of cloud systems which they carry, permit them to reconstruct, besides the surface synoptic weather map that is drawn from observations made at the ground, vertical sections of the atmosphere and to forecast their changes.

44. Systems.—The clouds associated with a cyclone are not distributed by chance but have a definite relation to the strength of the

system, the topography, the fronts, and the air masses involved. The cloud system associated with a cyclone may cover several states. The information to be derived from any particular cloud type will be greatly enhanced by a previous knowledge of the location of the entire cyclonic system together with the state of the visible sky as a whole. It is necessary to follow the evolution of the sky as a whole. The

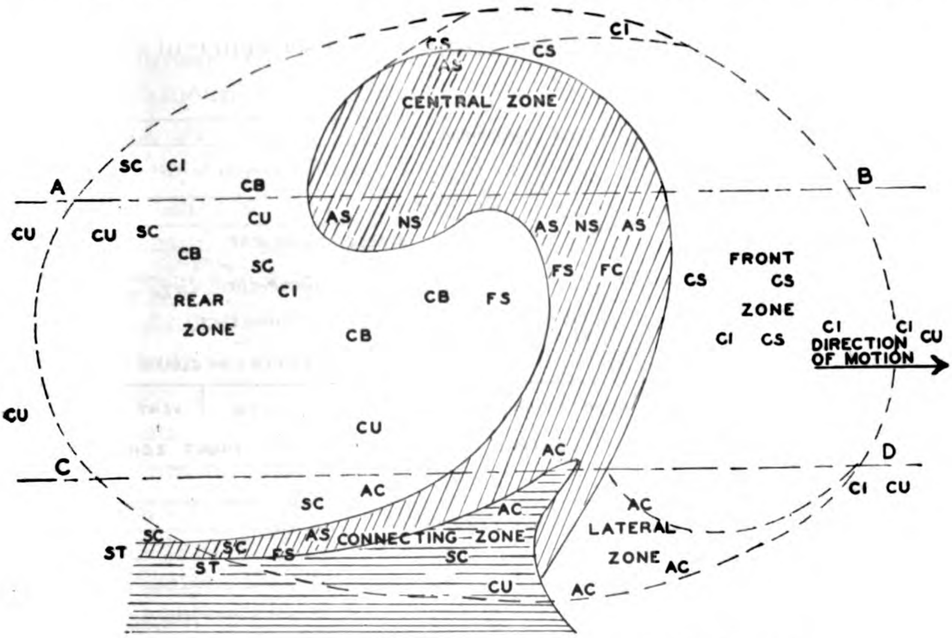


FIGURE 41.—Schematic diagram of an idealized cyclonic cloud system.

aspect of the sky is continually changing and many transitional forms exist between the different cloud types. It is relatively rare for the pilot to see typical clouds of one genus persist in the sky for any considerable period of time; he should continually watch the changes that are occurring.

a. Typical cyclonic cloud system.—(1) The diagram shown in figure 41, taken from the International Cloud Atlas, shows the distribution of cloud and sky types in the various sectors of a typical disturbance. Many clouds occur outside of cyclonic areas.

(2) Figure 42 represents vertical sections along the lines *A–B* and *C–D* in figure 41. The type of flying weather is indicated along the base of each section. Fronts have not been included since they are rarely seen.

b. Frontal cloud systems.—(1) Warm-front cloud systems are usually stratiform in character and occur chiefly in the warm air mass. When the warm air mass is conditionally unstable, as is characteristic of Tg and Pp air in the lower levels, the lift over the frontal surface is usually sufficient to release the instability. Cumuliform clouds growing out

of stratiform clouds result. Frequently the instability is sufficient to carry the moist, unstable air high into drier layers above that have fairly steep lapse rates. The result is towering masses of cumuliform clouds surrounded by clear air. They contain severe turbulence, icing zones, usually precipitation, and frequently thunderstorms. The surrounding air is smooth and they can be avoided during the day and usually at night. Warm-front clouds occur in parallel bands arranged symmetrically with the front. The sequence of clouds from

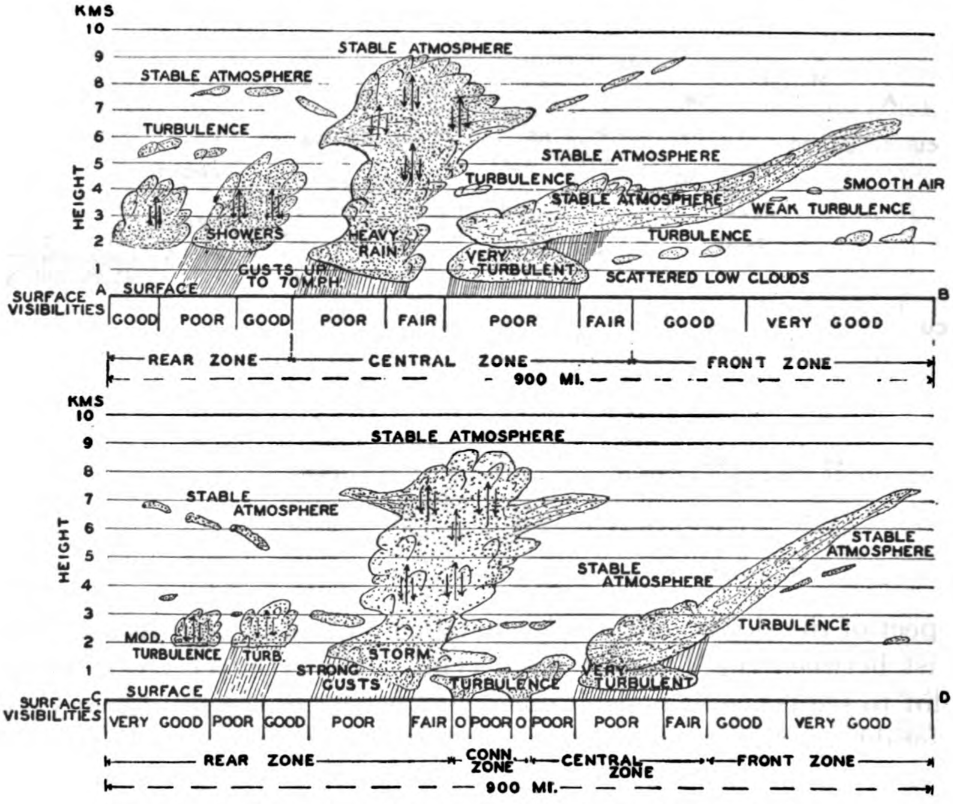


FIGURE 42.—Vertical sections of the cloud systems along the lines *A–B* and *C–D*.

the head to the rear of the system is cirrus, cirrostratus, then usually at some distance below, altostratus in one or more layers which in precipitation areas merge to form nimbostratus, and as the surface front is reached, stratus, and frequently fog. (See fig. 65.) Stratus, fractostratus, fractocumulus, and cumulus may develop in the cold air beneath the warm front. At night the stratus may lower to form widespread fog areas. Very thick stratiform cloud systems are not frequent or widespread. They usually occur in a narrow zone a short distance ahead of the surface front. The stratiform clouds more frequently form in distinct layers between which the pilot may fly with good horizontal visibility but limited vertical visibility.

(2) Cold front cloud systems usually occur in a narrow band above the surface frontal zone and in the warm air. The thickness and vertical extent of the clouds depend upon the activity of the front and the air masses involved. Along an active cold front underrunning conditionally unstable warm air, there is an almost continuous line of cumulonimbus clouds with thunderstorms. (See fig. 66.) This cloud system may be 30 or 40 miles wide and extend up to cirrus levels forming a great wall that is practically impenetrable with safety. Stratus, stratocumulus, and cumulonimbus often occur in the warm air ahead of an active cold front, particularly in the warm sector of a wave. The clouds in the warm air behind a fast moving, surface cold front dissipate rapidly as shown in figure 67. Cumulus humilis and fractocumulus are typical clouds in the cold air behind the front. When the cold air becomes sufficiently unstable by moving over a much warmer or moist surface, or both, cumulonimbus clouds develop in the cold air. These clouds produce scattered showers or snow flurries which may either be avoided, flown through, or flown over.

(3) Stationary fronts have typical warm front cloud and precipitation systems associated with them. They may cause precipitation, low ceilings, and low visibilities to persist in a given area for days at a time. Stationary fronts are the prime reason for the great floods in the Mississippi Basin.

(4) Occluded fronts carry a warm or cold front cloud system depending upon the type of the occlusion.

c. Flight path relative to a cloud system.—(1) The weather encountered during a flight depends upon the cloud systems traversed. It must be kept in mind that while the airplane is in flight, the cloud systems, although they are maintaining their positions relative to the cyclone, are moving with a velocity which is ordinarily about 30 miles per hour. Therefore, it is necessary to consider the relative motion of the airplane and the cloud system.

(2) Assume that a pilot has a weather map available which shows the location of the cloud systems, their direction of motion and rate of travel. In order to get a correct idea of the weather that he may encounter along the route to be flown, he must determine his trajectory relative to the movements of the cloud systems and attempt to reconstruct a vertical section that will show the weather along the route at the time he will be there. The main points that he must consider are the ceiling, visibility, thunderstorms, turbulence, and icing zones.

45. Photographs.—Photographs to illustrate types of clouds and states of sky are shown in figures 43 to 67, inclusive. Both aerial and ground photographs are included.

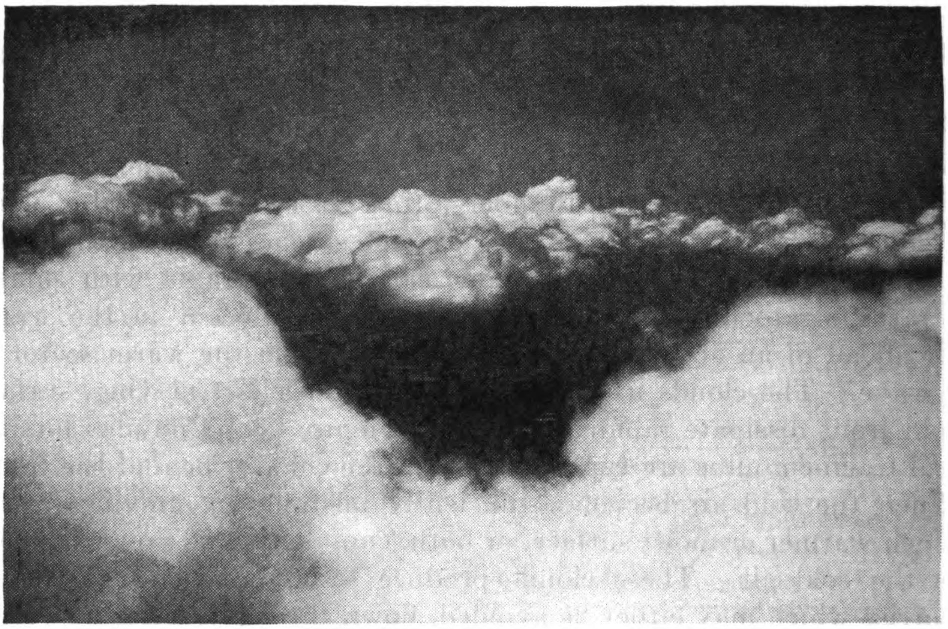


FIGURE 43.—Cumulus of fine weather (cumulus humilis). The clouds are scattered with definite horizontal bases and rounded upper surfaces. The diurnal period of convection is well advanced without much vertical development. Photograph taken near Grapeland, Tex., from 6,000 feet, April 30, 1939, at 1800 central standard time.

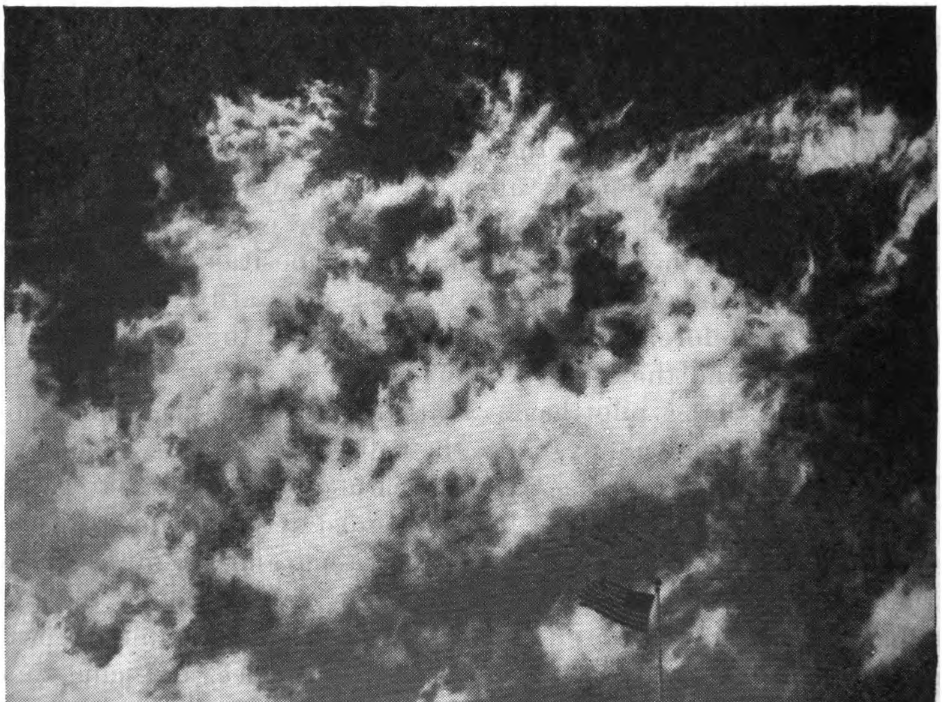


FIGURE 44.—Fractocumulus of fine weather. The clouds are broken up by the wind. The shadows are light, indicating that the clouds are thin. This form of fractocumulus must not be confused with the fractocumulus of bad weather which forms beneath nimbostratus or cumulonimbus.

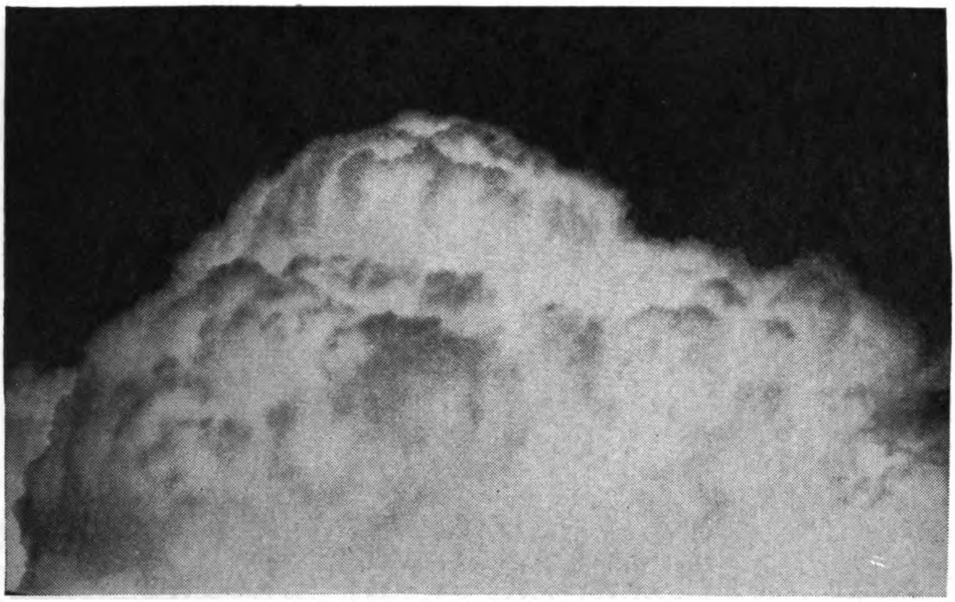


FIGURE 45.—Cumulus, heavy and swelling, without anvil top (cumulus congestus). The large cloud mass in the center has a horizontal, heavily shaded base and shows active vertical development with heaps in a "cauliflower" formation. The upper surfaces look hard and are clear cut, hence the central cloud mass has not yet reached the cumulonimbus stage.

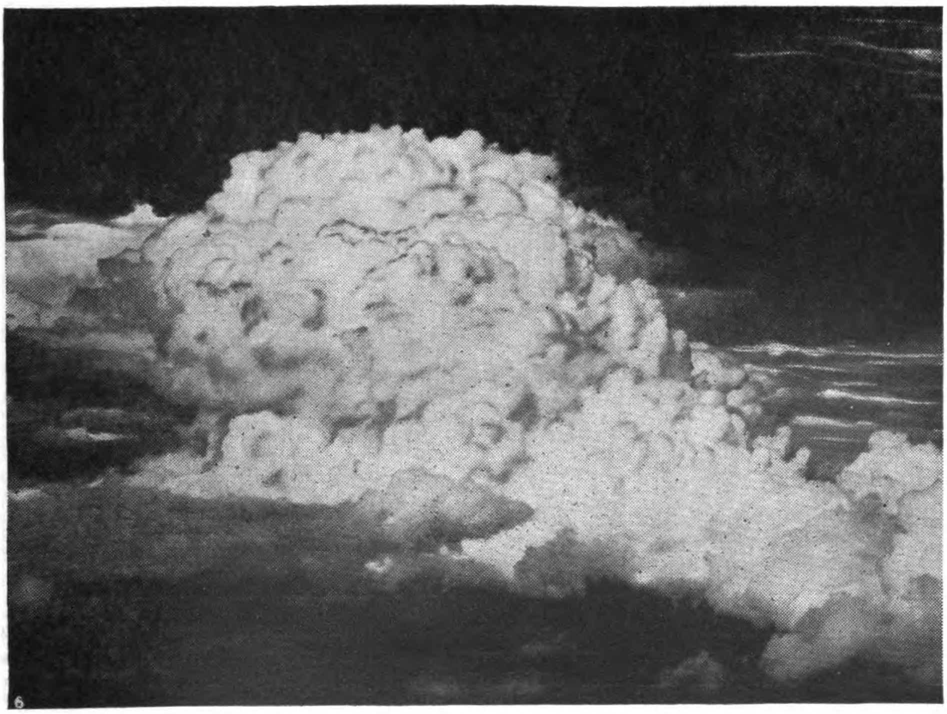


FIGURE 46.—Rapidly growing cumulus in tropical gulf air. Photograph taken 5 miles northwest of San Antonio, Tex., from 9,000 feet, June 14, 1938, at 1700 central standard time.

FIGURE 47.—Cumulonimbus with rapidly spreading top (cumulonimbus incus mammatus) and shower beneath. Clouds moving to left. Rapidly growing cumulus in foreground. Note dark cloud bases. Photograph taken 10 miles east of Randolph Field, Tex., from 4,000 feet, July 6, 1938, at 1400 central standard time.

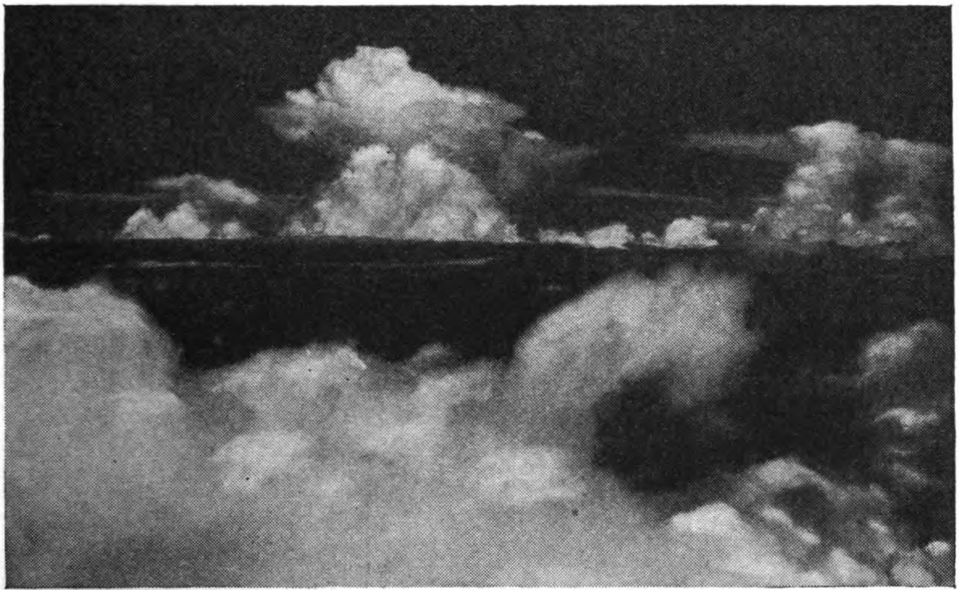


FIGURE 48.—Cumulonimbus with anvil top being penetrated by further cloud growth. The anvil consists chiefly of ice crystals while the portion of the cloud above is composed of supercooled water droplets and ice crystals. Cumulus and stratocumulus to the sides and in the foreground.

FIGURE 49.—Top of layer of stratocumulus. These clouds show dark shadows and large breaks or holes. There was a 3° C. inversion above the top of this layer, above which there was a thick isothermal layer. Photograph taken at Monroe, La., from 8,000 feet, April 30, 1939.

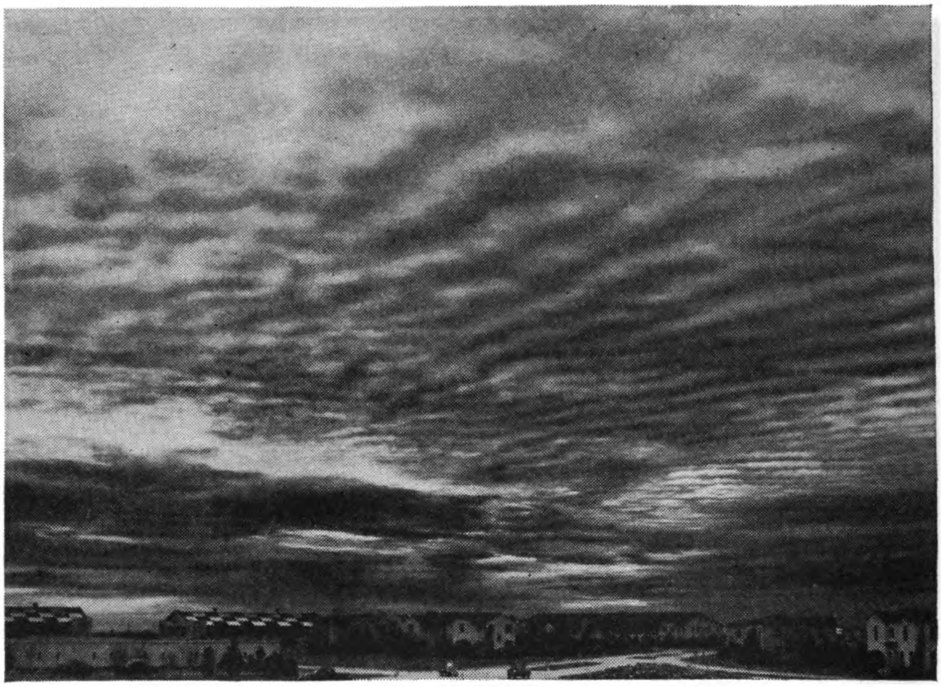


FIGURE 50.—Layer of stratocumulus. This layer is in rather regular waves or rolls with lighter semitransparent parts.

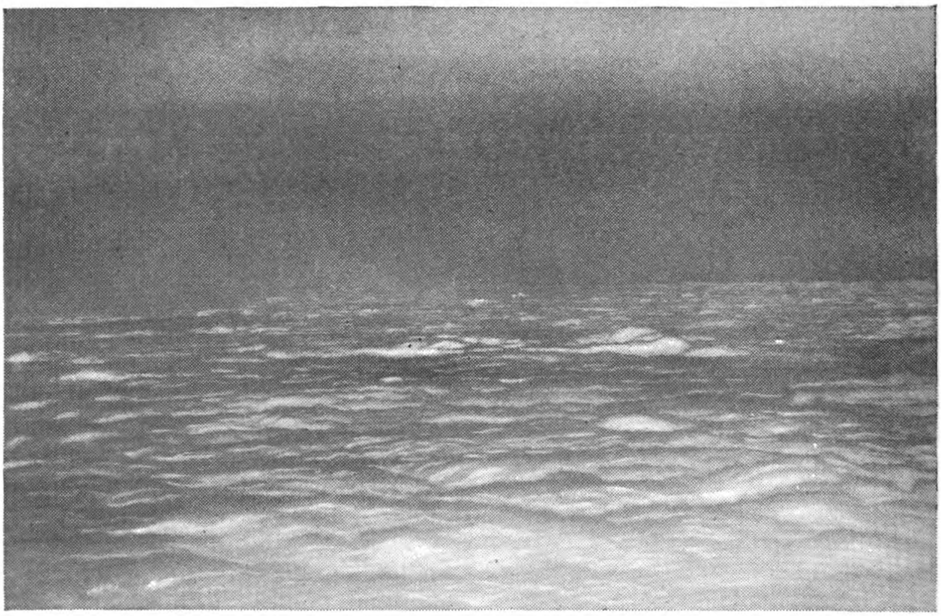


FIGURE 51.—Top of layer of stratus in tropical gulf air. There was a 2° C. inversion just above the top of this layer with an isothermal layer 6,000 feet thick above. Photograph taken 20 miles north-northeast of Barksdale Field, La., from 4,000 feet, April 24, 1939, at 0900 central standard time.

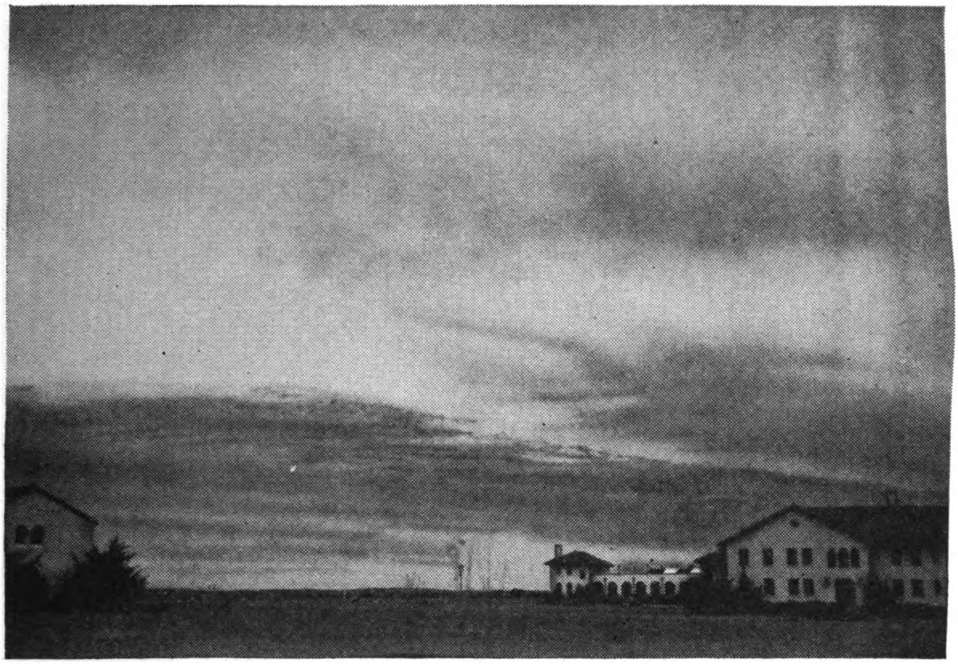


FIGURE 52.—Two decks of stratus forming in RPP air that has had a short trajectory over the Gulf of Mexico. Stratus forming ahead of the warm front of a stable wave. Waves or rolls dimly visible.

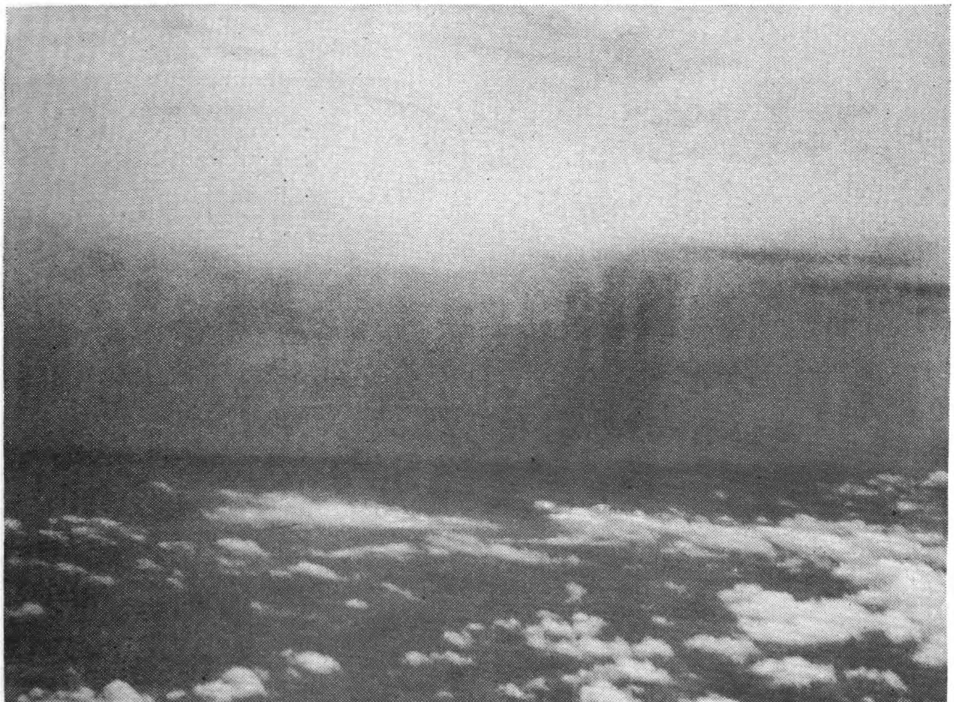


FIGURE 53.—Nimbostratus and low broken clouds of bad weather (fractocumulus and fractostratus) in "conditioned" tropical gulf air. The upper part shows the base of nimbostratus clouds from which heavy rain is falling with the lower broken clouds in the foreground. Photograph taken at Anderson, Ga., from 8,000 feet, April 29, 1939, at 1600 central standard time.

FIGURE 54.—Several layers of stratiform and cumuliform clouds in tropical gulf air during process of evolution from cumuliform to stratiform types. Photograph taken at San Antonio, Tex., from 6,000 feet, June 14, 1938, at 1700 central standard time.

FIGURE 55.—Altostratus merging into nimbostratus developed from cumulonimbus with cumulus and fractocumulus below, scattered showers, "conditioned" tropical gulf air. Photograph taken at Chesterfield, Tenn., from 9,000 feet, April 24, 1939, at 1100 central standard time.

FIGURE 56.—Typical altostratus, thin. This is a typical sheet of thin altostratus, distinguished from cirrostratus by the absence of halo phenomena. The sun appears as though shining through ground glass. Masses of fractostratus are below.

FIGURE 57.—Altocumulus in tufts resembling small cumulus clouds (altocumulus floccus) in TG air. Photograph taken at Randolph Field, Tex., May 7, 1939, 1830 central standard time.

FIGURE 58.—Altocumulus with vertical development (altocumulus castellatus) and snow trailers (virga) below layer of altostratus. Clouds formed by convergence and diurnal heating in "conditioned" TG air. Photograph taken southeast of Nashville, Tenn., from 9,000 feet, April 24, 1939, at 1330 central standard time.

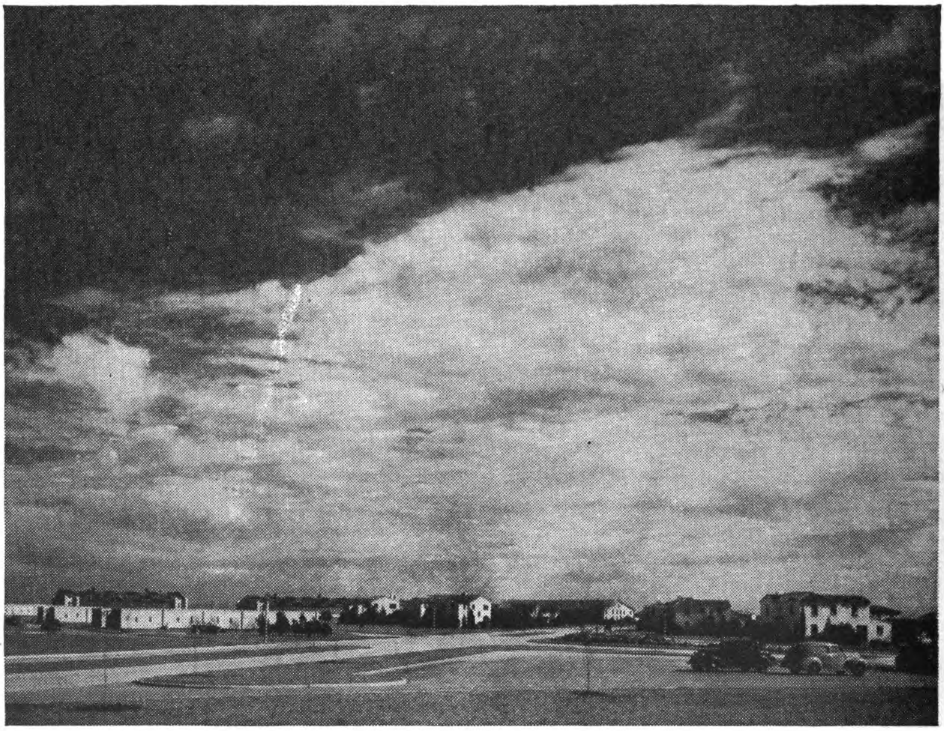


FIGURE 59.—Rear of cloud system associated with a slowly moving, weak cold front between PC and TG air, PC at the surface with TG aloft, clouds in TG. Altocumulus merging into altostratus and stratocumulus with lower stratus in the distance. Photograph taken looking southeast from Randolph Field, Tex., January 21, 1939, at 1230 central standard time.

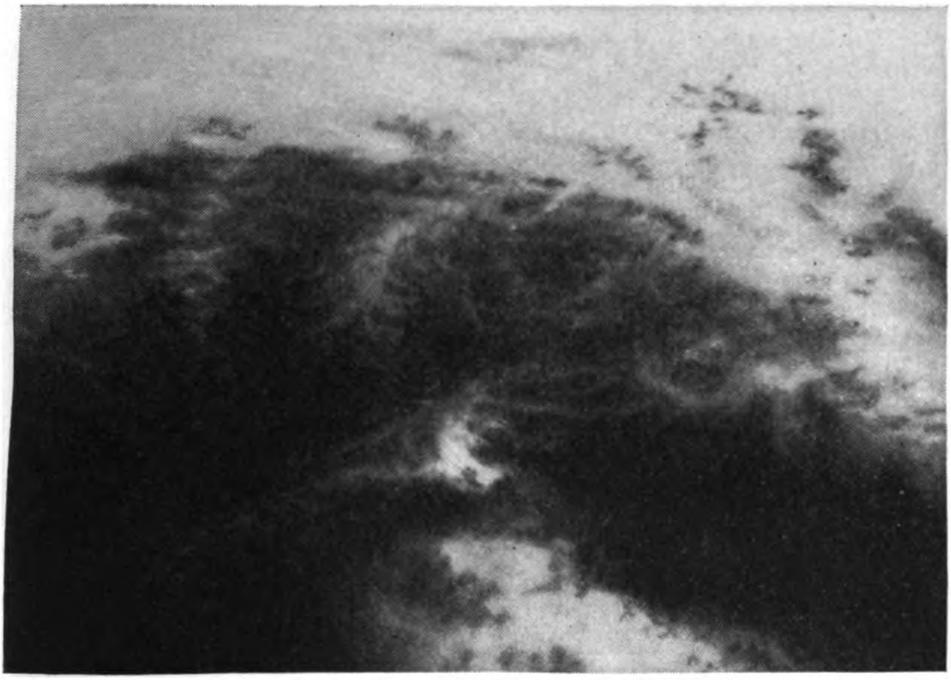


FIGURE 60.—Cirrus, fine, with disordered arrangement in zone of convergence aloft. Photograph taken looking northwest from Somerset, Tex., from 6,500 feet, March 1, 1939, at 1612 central standard time.

FIGURE 61.—Cirrus developing from cumulonimbus. Rear view of severe thunderstorm along a cold front between Pp and Tg air. Heavy hail, strong winds, and small tornadoes with this system caused damage over a wide area. The front moved slowly to the southeast. Photograph taken looking northeast from Randolph Field, Tex., May 8, 1939, at 1830 central standard time.

FIGURE 62.—Cirrocumulus with trailers of snow. The trailers are oriented parallel to the wind while the waves in the cirrus are perpendicular to the wind.

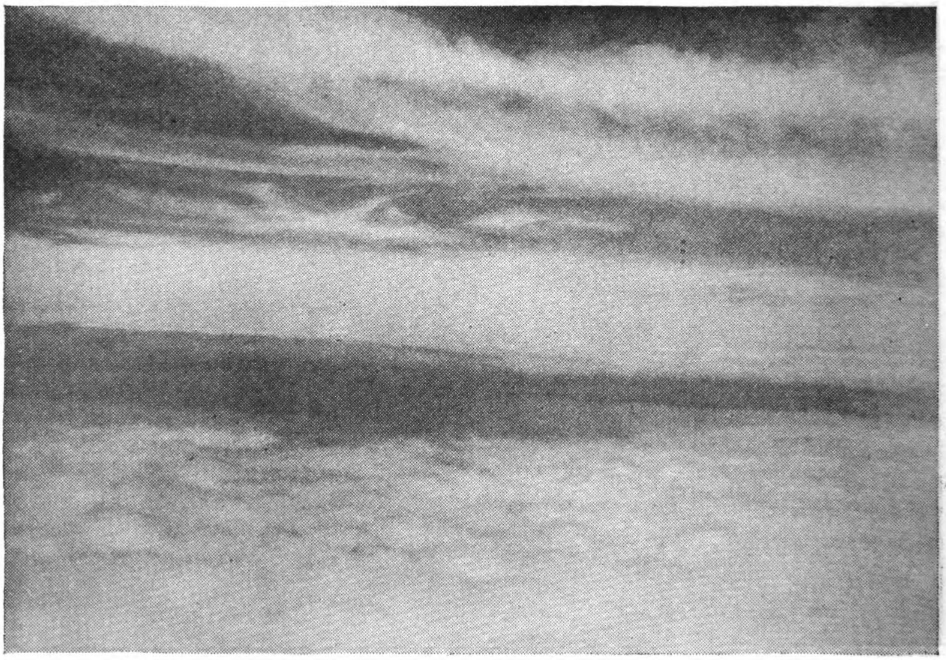


FIGURE 63.—Cloud system ahead of a TG warm front. Cirrus and cirrostratus above, altostratus in the middle, and a deck of stratus below. Photograph taken about 30 miles south of Randolph Field, Tex., from 6,200 feet, looking southeast. March 1, 1939, at 1413 central standard time.

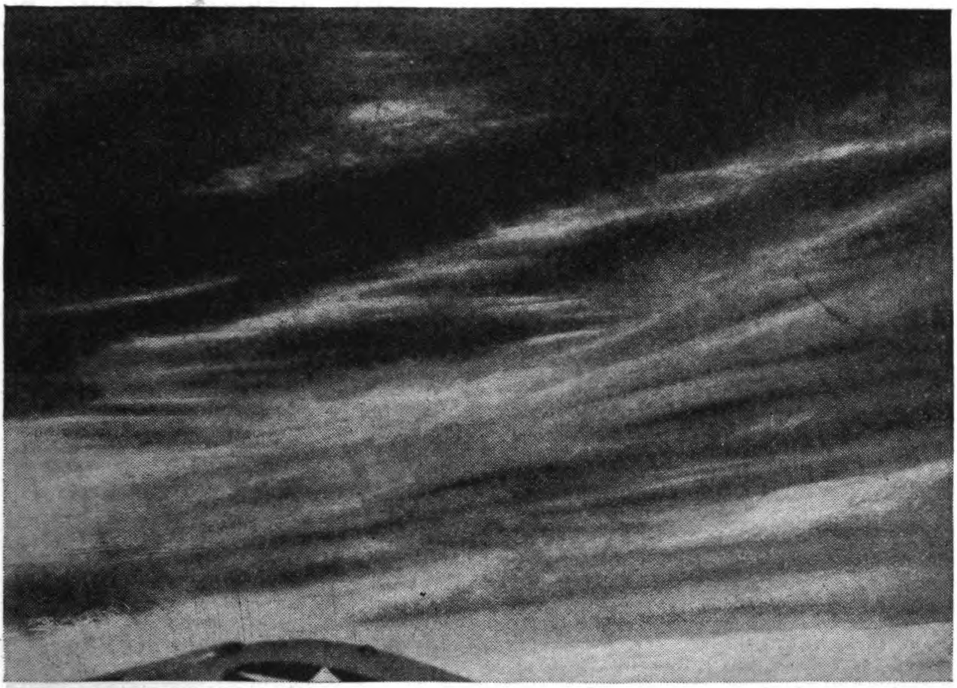


FIGURE 64.—Cirrus merging into cirrostratus above a deck of stratus. Photograph taken about 10 miles southwest of San Antonio, Tex., from 6,800 feet, March 1, 1939, at 1615 central standard time.

FIGURE 65.—Lowering stratus ahead of a warm front.

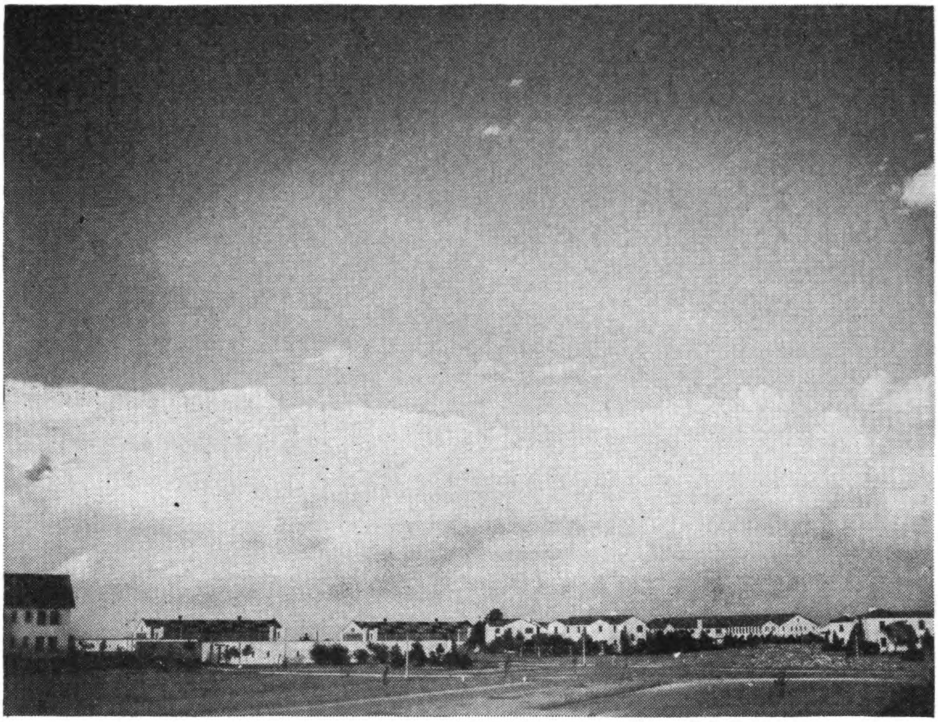


FIGURE 66.—Rear view of line of cumulonimbus clouds and thunderstorms along a cold front. Photograph taken looking east from Randolph Field, Tex., May 8, 1939, at 1830 central standard time.

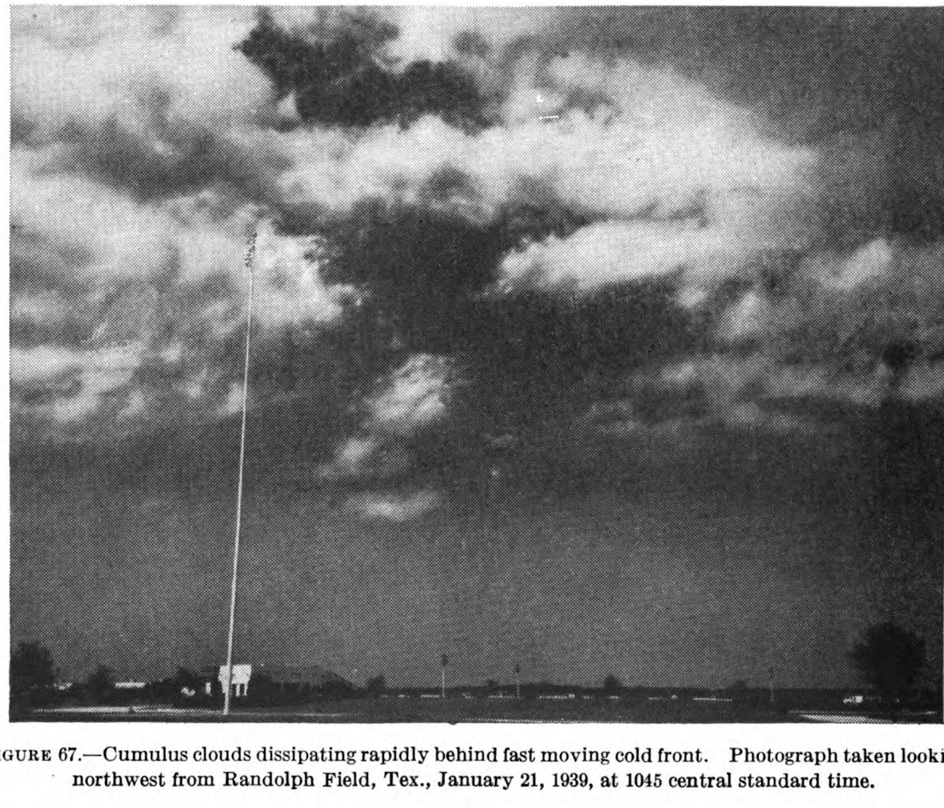


FIGURE 67.—Cumulus clouds dissipating rapidly behind fast moving cold front. Photograph taken looking northwest from Randolph Field, Tex., January 21, 1939, at 1045 central standard time.

46. Wind direction from clouds.—*a. General.*—Relative wind velocities and frequently wind directions at various levels may be determined from aircraft while in flight without visual reference to the ground, according to a recently developed theory. This theory is based upon the assumption that since different portions of a cloud usually contain different configurations, these different configurations should reveal the flow structure of the moving fluid which contains them. Determination of wind direction from clouds without visual reference to the ground may be made from—

(1) Motions within clouds.

(2) Static appearance of a portion of a cloud such as a curl or hook.

(3) Shape of clouds.

(4) Orientation of clouds.

b. Motions within clouds.—It is well known that due to surface friction, wind velocity normally increases with altitude, according to the Ekman spiral (fig. 26) throughout the layer from the ground up to the gradient, or roughly, 2,000-foot level. It immediately becomes apparent that the upper portions of clouds within this layer will normally move faster than the lower portions. Therefore, careful scrutiny of the lower clouds, even while in flight, will reveal this relative motion and at once give the wind direction at the level observed. Only so much of the cloud as will give this relative motion, perhaps a fragment apparently 1 yard long or even a short light or dark streak, need be watched. To the benefit of a pilot above the clouds, the tops of clouds give better indications of wind direction than the bases.

c. Cloud curls.—(1) When the increase of wind velocity with altitude is sufficient to cause turbulence, the cloud will be filled with vortices or curls. The tops of the larger curls move with the wind. The rate of rotation and the amount of relative motion give a measure of the rate of increase of velocity with altitude in these low clouds.

(2) During the day there are almost always some convections from the ground in the lower levels of the atmosphere. Normally they are quite pronounced. In summer they often reach to 12,000 feet in some parts of the United States. These upward motions combine with the prevailing wind to fill the air with vortices and resultant bumpiness up to the top of the convective layer. The distance that these convections will penetrate an overlying stable layer depends upon the degree of stability of the upper air and the strength of the convections. They have been observed in clear air 3,000 feet above the base of the stable layer and will therefore often influence the motions in cumuliform clouds that may be in surrounding stable air.

(3) Air moving upward in clouds cools at the prevailing saturation adiabatic lapse rate and cloud formation is aided. Thus the rising portion of a curl is its most dense portion. When the curl turns downward, it is heated at the same rate, which tends to dissipate the sinking portion. Visible curls are at the surface of the clouds and are penetrating unsaturated air which also tends to dissipate the cloud. The result is protruding curls which are well defined in their rising portions. The dissipating curl or hook has a very characteristic appearance and may be seen at distances from a few yards up to more than 75 miles depending upon the size of the curl. With an increase of wind

FIGURE 68.—Clouds moving from right to left. Lean of numerous small wisps at top edge of clouds shows wind direction. Tops of wisps move faster than the bases.

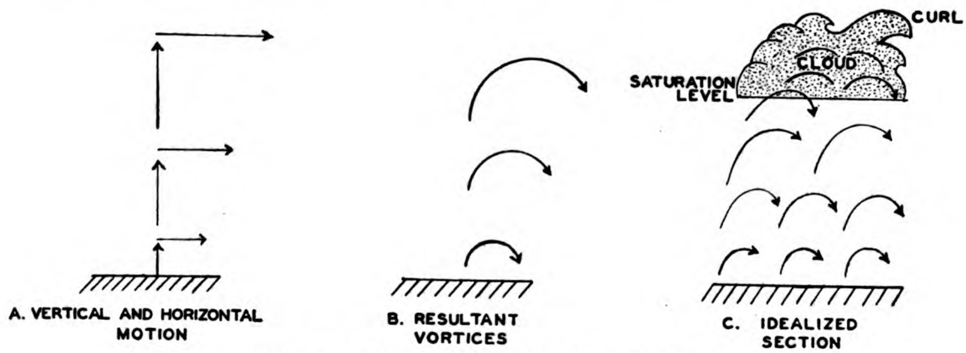


FIGURE 69.—Development of turbulence and curls.

velocity upward, that is, when the vertical velocity gradient is downward (↓), the hook points in the direction of the wind.

(4) In considering levels above 2,000 feet, it must be borne in mind that wind velocity does not always increase with elevation although it is generally true that it does. When wind velocity decreases with elevation, the curls will rotate opposite to their normal direction and the hooks (reverse curls), will point up wind. If the pilot is not lost, it matters little which way the curls are rotating as they will always indicate the altitude within the cloud levels at which the wind is most favorable.

d. Shape of clouds.—(1) Cirrus clouds are strung out in the direction of the wind with the forward portion often apparently raised, sometimes forming a tuft. Their fibrous appearance readily reveals the direction in which they are moving. Distinct angles in the fibers indicate a change of wind direction at that point and are a sign of convergence. Balloon runs rarely reach up to cirrus clouds and their distance and character usually make it difficult even for a ground observer to determine their direction of motion by reference to some ground object.

(2) Other stratiform clouds are the most difficult clouds from which to determine wind direction by their shape. When they are in solid layers, the best information may be gained from a detailed study of their upper and lower surfaces. When broken or isolated, the portion in the strongest wind will move ahead of the rest of the cloud giving it a leaning appearance.

(3) When the wind increases aloft, the up wind edge of cumuliform clouds is well defined; it slopes upward and forward with the wind. On this side of the cloud only the rising portions of the curls are visible. The down wind edge has a frayed appearance and also slopes generally upward and forward. On this edge the dissipating portions of the curls are visible. The whole cloud has a tilt down wind and a swept-over appearance as though it had been lightly brushed over. Rapidly building cumuli are usually well defined on all edges although by far the major portion of the curls, even on the up wind side, have their characteristic rotation. The large curls give the impression of a bull with its head lowered for a charge. Very rapidly building cumulus is identified by its columnar structure as well as the relative motions which are plainly visible from the ground or the air. When the water droplets begin to change to ice crystals at the zero isotherm or above, the cloud begins to take on a fibrous appearance, curls are less well defined and larger features become more important. Beneath a stable layer, the cloud spreads out in all directions forming the anvil

of the thunderhead, but the winds aloft will cause the down wind portion of the anvil to be greater in extent, often stringing it out into

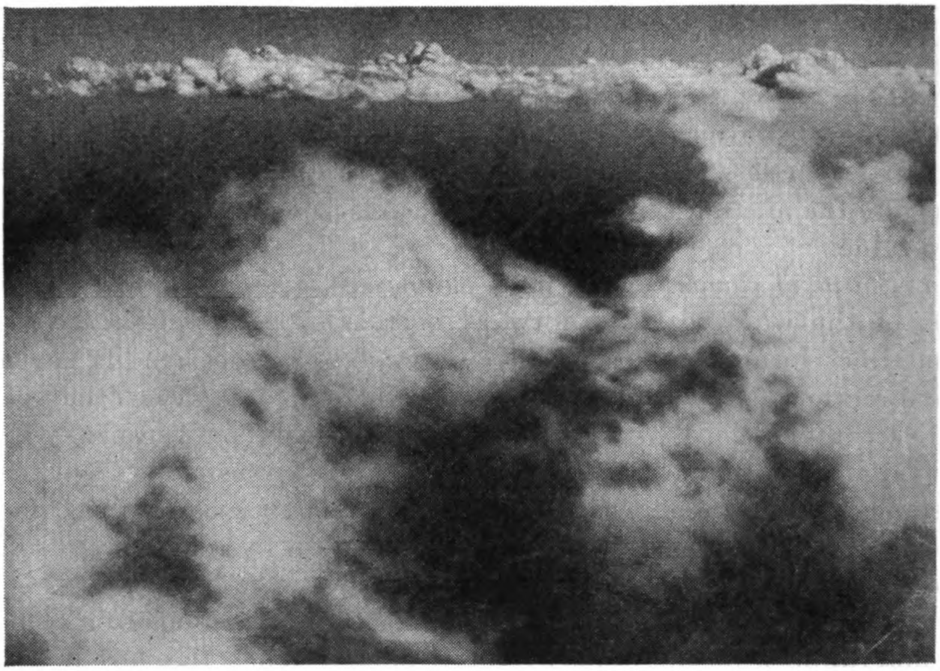


FIGURE 70.—Characteristic curl.

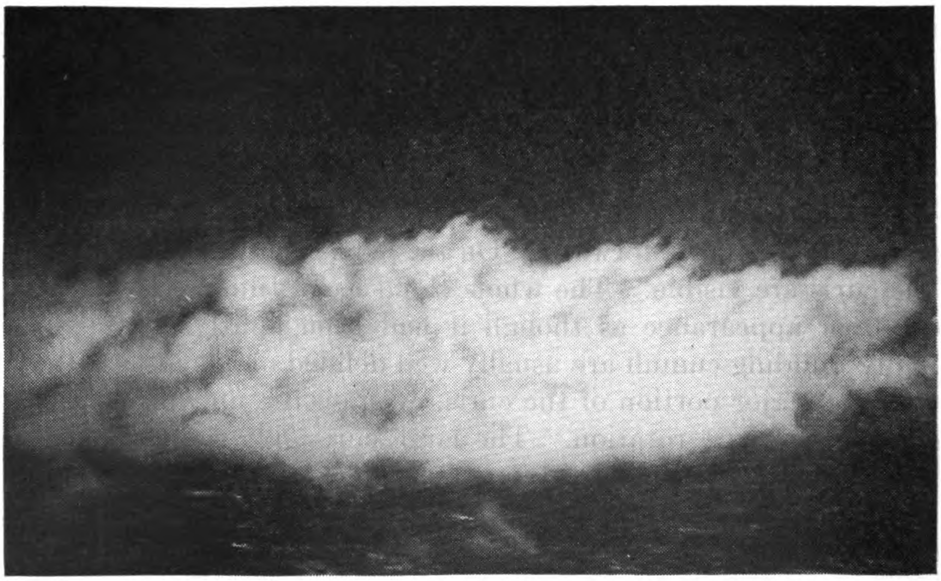


FIGURE 71.—Reverse curls.

cirrus. Wind direction at the top of a thunderhead may readily be determined within reasonable accuracy at distances greater than 100 miles.

FIGURE 72.—Cirrus clouds moving from right to left.

FIGURE 73.—Shape of small stratocumulus clouds indicating movement from left to right.

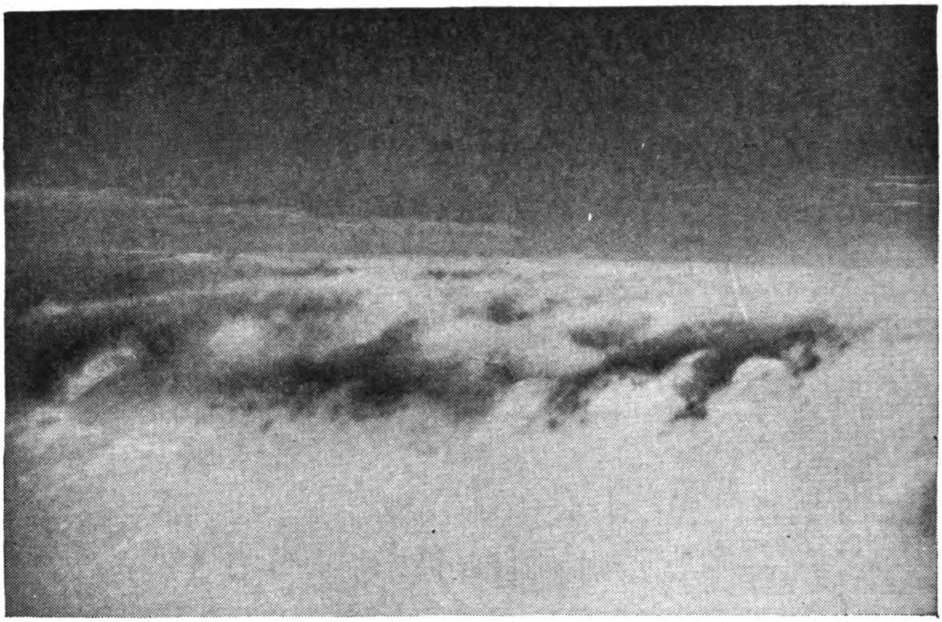


FIGURE 74.—Wisps on top of stratus deck giving wind direction.

FIGURE 75.—Tilt of cumulus cloud showing movement from left to right; columnar structure in foreground indicates rapid vertical growth.

FIGURE 76.—Cross wind view of cumulus cloud showing curls.

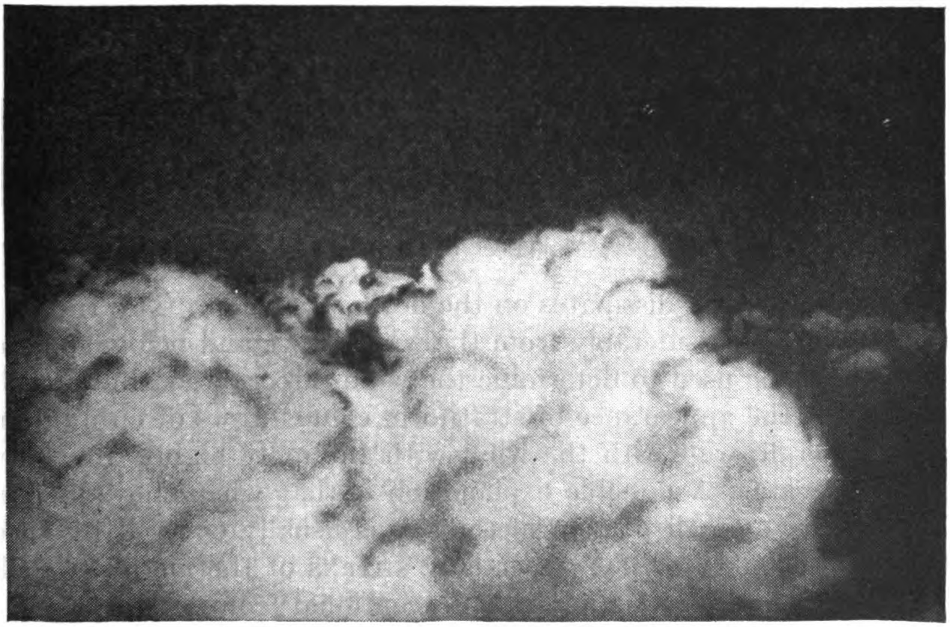


FIGURE 77.—Down wind view of same cloud as in figure 75. Note absence of visible curls.

e. Cloud orientation.—(1) Clouds often appear in rows or exhibit a slanting parallelism. Stratiform clouds sometimes appear in well-defined rows or rolls. These rolls are really waves along a minor discontinuity surface above and below which the wind may be in the same or different directions. These waves are known as Helmholtz waves and usually are only a few hundred yards in amplitude. The bands of clouds run only the crests of these waves with clear air in the troughs. Much smaller waves frequently occur. Since the waves form at right angles to the resultant wind direction, the rows of clouds are perpendicular to the wind. The cloud roll forms on the up wind

FIGURE 78.—Wind in the upper levels from the right, TG air. Photograph taken looking east from Randolph Field, Tex., from 6,000 feet, June 14, 1938, at 1700 central standard time.

side of the crest and dissipates on the down wind side. The resulting wind may vary considerably from the wind above and below so other criteria must be used to determine the wind direction at these levels. Contrary to the appearance of stratiform clouds, rows of cumuliform clouds generally run with the wind with the more highly developed clouds up wind. A possible explanation is that when they do form in rows, only a small portion of the sky is usually covered by them which would indicate that either only streaks of the air mass could support cumulus clouds or that exceptional convective activity existed over a relatively small area. The tilting of individual clouds gives a slanting parallelism to a whole group of clouds.

(2) The best view for determining wind direction from clouds is cross wind. When viewed up or down wind, the line of sight is parallel

to the plane of rotation of individual curls and is in line with any general tilting of the clouds, hence these features are obscured. Clouds have a characteristic appearance for cross wind, up wind, and down wind views. The down wind view reveals well-defined surfaces sloping up and away while the up wind view shows the more ragged, frayed, and darker portions of the clouds.

(3) Wind direction determination from a group of clouds is more reliable than from an individual cloud. The shape, orientation, and motions of clouds may be determined by a single glance and the entire

FIGURE 79.—Helmholtz waves in stratocumulus. Wind is perpendicular to crest or trough lines, from left to right.

visible portion of the atmosphere may be seen very quickly. It is advisable to scan the entire horizon before coming to a definite conclusion as to wind direction or the relative motion at various levels. Experience has shown that optical illusions play an important part, especially with beginners. A determination made from a single cloud may be correct to within only 180°. An average direction, determined upon after glances have been made in several directions will bring the possible angle of error down to small limits. Quite often several glances will yield no definite information but it is rare that a search of the entire sky will not give the information sought.

(4) The same principles used with clouds may be used with smoke, dust, or thick haze. In thick haze, vortices may be seen from the

ground up to the base of the clouds. Curls that originate below the saturation level and extend above that level will be cloud in the upper part and haze in the lower portion. The direction that smoke columns

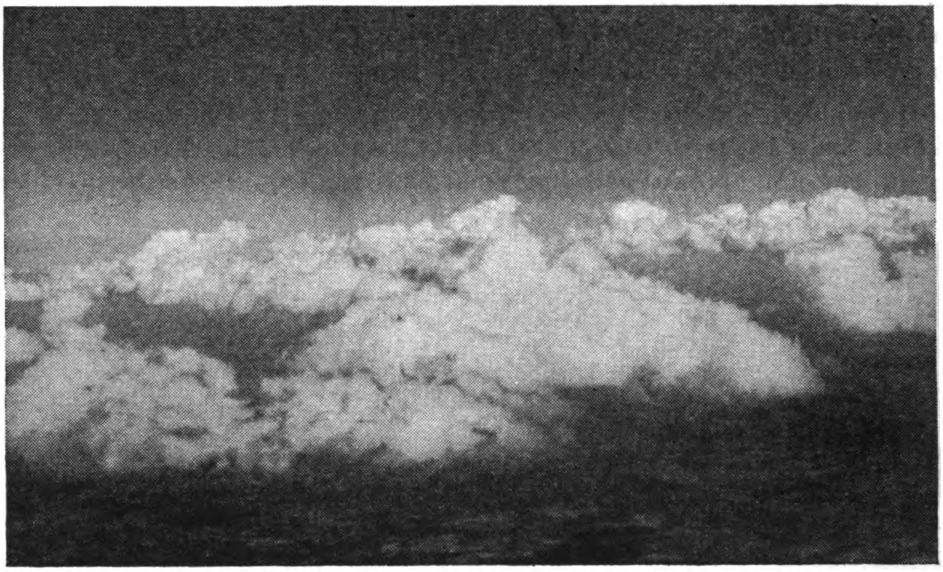


FIGURE 80.—Up wind view of cumulus clouds.

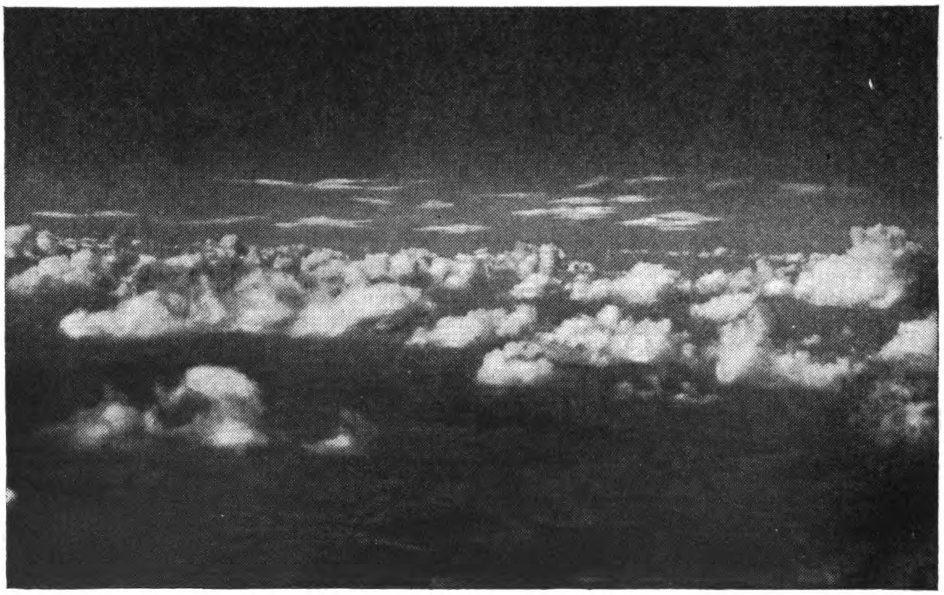


FIGURE 81.—Down wind view of cumulus clouds.

lean is an important clue and the stringing out of smoke from a fixed source is almost an ideal wind indicator.

(5) At night, surface cooling stabilizes the air near the ground and reduces surface velocities considerably so that under an existing

pressure gradient, winds at about the 2,000-foot level pick up proportionally. If low stratus exists, the resulting vertical velocity gradient causes turbulence with numerous curls in the stratus. The curls may be seen easily in moonlight. Cirrus and other clouds above the convective layer have the same general appearance at night as in the daytime except that they appear to thin out and quite frequently disappear entirely at night.

(6) A well-defined edge of a layer or mass of clouds is usually perpendicular to the direction of motion of the clouds. Advancing

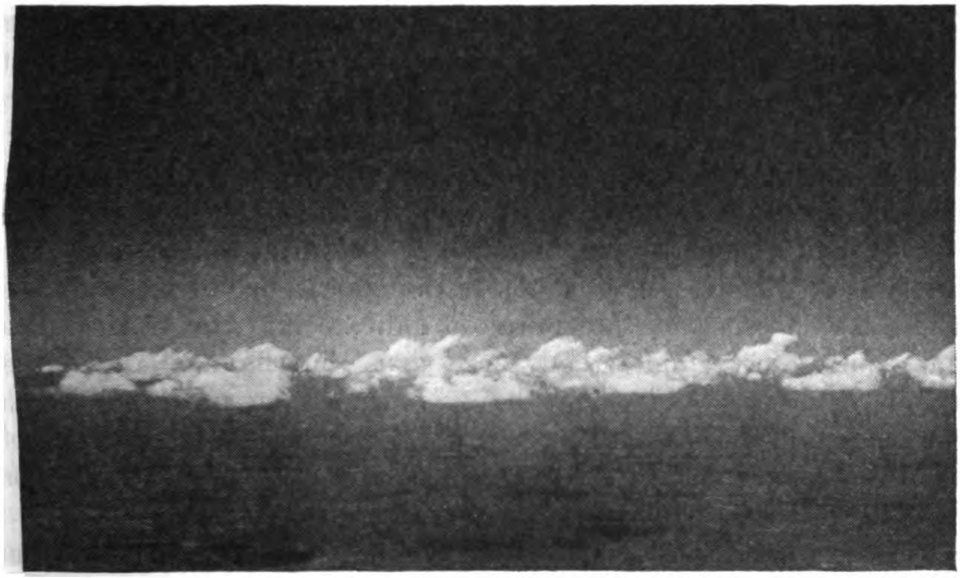


FIGURE 82.—Cross wind view of cumulus clouds. Figures 79, 80, and 81 show the same group of clouds. Wind decreases upward at cloud levels.

clouds have an appearance of strength that trailing clouds do not have. Clouds near the leading edge may be seen to grow and thicken while the trailing clouds get thinner and dissipate. Not only wind direction but the direction to a storm center or a clearing area may be learned from the orientation and appearance of the edge of a cloud mass. For example, a hurricane was known to exist in the Gulf of Mexico but its location was not known due to lack of ship reports. The leading edge of the advancing cirrus clouds formed an arc that was clearly visible from the ground when it was about 150 miles from Randolph Field. A mental radius drawn to this ring together with the estimated distance of the cirrus clouds ahead of the center gave the location of the storm center to be about 400 miles south southeast of Randolph Field. Later map data proved this estimate to be approximately correct. A series of such observations on a different

hurricane gave the direction of motion of the storm center as well as the distance away.

47. Formation and dissolution.—Very low clouds will always be one of the greatest hazards to aviation because they hinder the landing of aircraft. Higher clouds are hazards when they limit visibility directly or by precipitation, cause malfunctioning of radio, contain severe turbulence, thunderstorms or icing conditions, and they contribute to a hazard when they aid in the formation of very low clouds.

a. Cloud formation.—Clouds form when the air is cooled sufficiently. The air may be cooled due to lift or radiation, or both. Therefore, clouds tend to form in areas of convergence and on the windward slopes of mountains. Uniform lift or radiation originally form stratiform clouds. Irregular lift, as in convections, forms cumuliform clouds. They increase over land during the day. Uniform lift is usually accomplished over frontal surfaces. Hence, when the clouds that appear first are stratiform, there is strong evidence there is overrunning and a front is being approached. Continued increase in the thickness of the stratiform clouds or the appearance of several layers of clouds and especially precipitation indicate that the front is near. Many pilots have understood these signs, but have changed their original plan too late. They have continued on until one of the many possible hazards has made further progress in the given direction impossible and then, not knowing the synoptic situation, they have not known which way to turn. "Turn back" is still a good rule but not an infallible one because clouds do move and form. Clouds may form at any time during the day or night because the wind blows 24 hours a day.

b. Cloud dissolution.—(1) Cumulus clouds dissolve upon the approach of a warm front surface. Cirrus or cirrostratus clouds means the shrinking and flattening out of cumulus clouds. They undergo a complete transformation and become stratiform in character. The same effect is produced in the evening when diurnal convections cease. The typical clouds formed by this process are—

(*a*) *Stratocumulus vesperalis.*—The lower part of the cumulus cloud spreads out and the top dissolves.

(*b*) *Stratocumulus cumulogenitus.*—The top of the cumulus cloud spreads out and the lower part dissolves. This type occurs frequently in the afternoon after showers.

(*c*) *Fractocumulus—fractostratus.*—Low ragged clouds.

(2) Rain causes the condensation level to become irregular and hence several cloud levels may be expected. Clouds through which precipitation is falling become ragged and uneven at their bases.

(3) Low stratus clouds not in a frontal zone may break up after sunrise and disappear later in the day. Even in frontal zones, ceilings will usually lift until the diurnal maximum temperature is reached. Over land, both main types of clouds except fog and low stratus tend to dissipate at night. Over water, the convective clouds increase at night and decrease during the day. Adiabatic heating due to subsidence will dissipate clouds readily. Therefore, all clouds tend to dissipate in an area of divergence.

c. Trend.—What the pilot wants to know concerning his route and destination is not only what exists along the route yet to be covered, but what the weather will be at the time of arrival. In other words, the trend of the weather is the desired information. One of the best ways to determine the trend is to determine whether the cloudiness is increasing or decreasing. Clouds often change so gradually that the change goes unnoticed by the casual observer. A check may be made by picking out an individual cloud and carefully noting what is happening to it or by estimating at intervals the amount of cloudiness in tenths of sky cover, then comparing estimates. There are several other methods such as noting the change in the type of clouds, beginning or ending of precipitation, change in type of precipitation, keeping the time of day, in relation to what is expected to happen, in mind, changes in topography, whether the air is becoming cooler or warmer, whether the ground is wet, dry, or snow-covered, whether the air has been made stable or unstable by recent passage over bodies of water, and most important, whether it is a cold or warm air mass and which direction it is moving, together with its relation to adjacent air masses or bodies of water.

Section VI

AIR MASSES AND FRONTS

48. General.—*a.* In synoptic meteorology, knowledge of the types of air masses and their characteristics is essential to a forecaster or to a pilot. An understanding of the source of the air mass, the properties derived from that source, and the modifications brought about in these properties as the air mass moves away from its source, will enable the pilot to visualize the weather phenomena he would encounter while flying in that mass.

b. Since most flying is done in air masses, a discussion of the flying characteristics of each air mass is of paramount importance. Except for fog, instability weather, dust, and other similar air mass hazards, most of the flying in air masses away from frontal zones will be contact. However, most severe weather results from the interactions between two dissimilar air masses and occurs in frontal zones. Frontal weather for North America is discussed in sections IX and X.

c. Since the properties of an air mass vary considerably from summer to winter, each North American air mass is discussed in sections VII and VIII.

49. Basic elements of forecasting.—In an attempt to arrive at a reasonable conclusion as to what to expect further along his route, the pilot must keep the following three basic elements in mind:

a. Physical characteristics of air masses involved.—Before take-off, he should gain from the forecaster and from the weather map a general picture of the weather situation to include the air masses and frontal zones that he will encounter. He should also learn the history of those air masses, their physical characteristics, the existing weather and what is causing it, and the directions of motion of air masses and fronts along the route. This information should be continually supplemented in flight by observation and radio weather reports.

b. Expected movements.—The forecaster's estimate of the amount of movement of the fronts and air masses should undergo constant check. His direct information is limited to reports from scattered stations along the route, whereas the pilot has the opportunity to get a continuous picture of the trend of events. The pilot is best able to do this by taking into consideration the direction and velocity of the wind, movement of pressure systems, evolution of cloud systems, and movement of fronts. By the use of radio weather reports, it is possible for him to keep track of the weather for hundreds of miles in all directions. These reports may have little meaning if he is not schooled in their proper use, but once he learns how to interpret them in relation to the synoptic situation, they will become of tremendous benefit in helping him to make a proper estimate of the weather that he will encounter.

c. Physical changes occurring during the time of flight.—The physical properties of the air masses are continually changing. Fog and very low clouds at a given time are no proof that they will be there an hour later, and vice versa. Probably more forecasts have not been verified because of failure to carefully consider this point than for any other one reason. Sunset is a time that is particularly critical, since air masses frequently change their basic type from cold to warm after the sun goes down. Another point in this connection is that when flying east, darkness comes sooner than at the point of take-off. The difference in time may be enough to cause changes that might not otherwise be expected.

50. History of air masses.—The determination of the physical properties of air masses consists of gaining information of a number of physical elements, such as temperature, which change with the progress of time. The study of the life history of an air mass involves the following factors: Source of the air, trajectory that it has followed in reaching its present position, and length of time that it has been on its way or its age.

a. Source.—(1) The concept of an air mass is fundamental as all weather results from air mass or frontal phenomena. An "air mass" is an extensive portion of the earth's atmosphere that approximates horizontal homogeneity. This means that if upper air soundings were made at two widely separated locations within an air mass, the data obtained at the two stations would be the same, level for level. This explains the use of the word "horizontal." The atmosphere is not uniform in a vertical direction except possibly in some portions of the stratosphere. Temperature, pressure, and humidity decrease more or less regularly with height. Actually, in the troposphere, the air masses are never quite homogeneous horizontally. However, any change in the characteristic properties of an air mass between various points in the mass will be quite gradual and continuous in nature. Figure 83 shows three actual soundings within an air mass at three widely separated points. If, however, a convergent flow develops within the mass and tends to create a sharp transition zone where the values of some property show a rapid change, that portion of the atmosphere is no longer in one air mass but contains portions of two air masses. These air masses are separated by a discontinuity surface or frontal zone. Frontal zones of this type arising within a given mass of air are the exception rather than the rule, but occur quite frequently in cold polar masses moving southward. Such transition zones always arise in the atmosphere where convergent flow develops

between air masses having different properties. They are extremely important in any consideration of the weather.

(2) The formation of an air mass takes place over the earth's surface wherever the atmosphere remains at rest or nearly so over a large area having uniform surface properties for a period of time

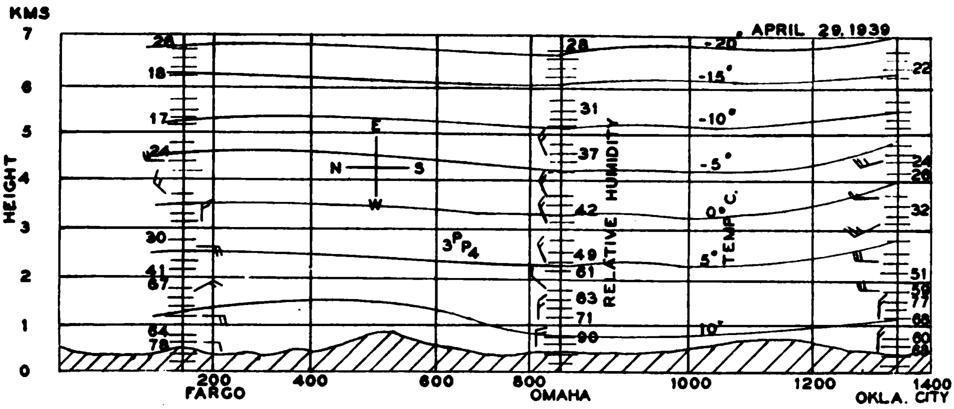


FIGURE 83.—Horizontal homogeneity of an air mass.

sufficient for the structure of the atmosphere to reach equilibrium with respect to the surface beneath. Such an area is a source region. Large areas where rather sluggish air movements exist are the subtropical high pressure belt and the polar regions where semipermanent

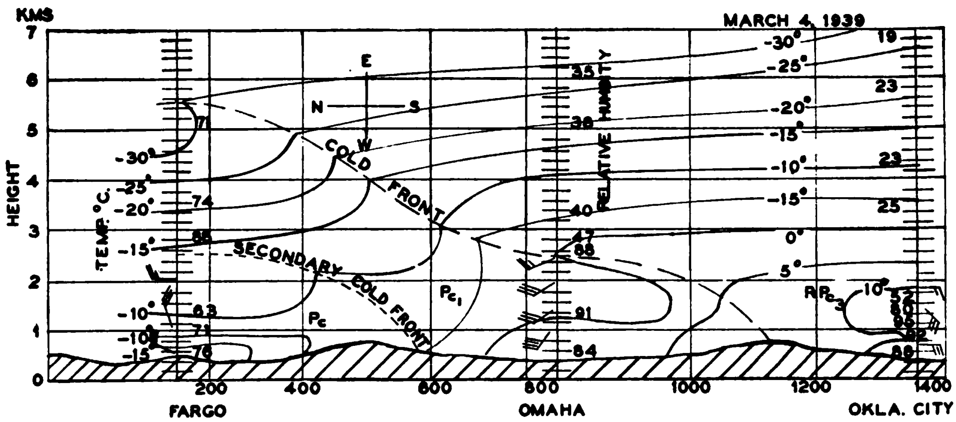


FIGURE 84.—Cross section through different air masses.

anticyclones tend to develop over ice- and snow-covered areas. Semipermanent anticyclones are usually the source regions for the North American air masses. Cyclones move too rapidly to allow the air within them to acquire the characteristics of the surface beneath.

b. Trajectory.—The path that an air mass follows when it moves out of its source in polar or tropical regions determines what its characteristics will be when it reaches the middle latitudes. The

modifications which take place are a function of the physical properties of the surfaces over which its trajectory carries it. The chief points to be considered are whether the path is colder or warmer, more moist or drier than the source region.

c. Age.—A polar current that has moved rapidly southward will vary considerably in its characteristics from one that has taken a much longer time. Properties absorbed at the surface are distributed gradually upward. A fresh polar mass will be modified in its lower levels but not in the upper ones. The height to which the modifications take place depends entirely upon the surface passed over and the age of the air mass. The stability of an air mass is determined by the length of time it has been over a given surface, since a warm air mass becomes stable over a cold surface and a cold air mass becomes unstable over a warm surface.

51. Classification of air masses.—*a.* Any classification of air mass types must be based fundamentally on the air mass source region, with perhaps a subclassification based on later modifications of the source properties. The air mass sources fall naturally into two groups, the tropical or subtropical and the polar or subpolar. The classification may be carried further by the subdivision of the polar and the tropical source types into continental and maritime groups. Since the uniform source regions are always entirely continental or entirely maritime, and since this is the essential difference between source regions in the same latitude, this distinction furnishes a satisfactory basis for a general grouping of the air masses from each latitudinal zone. Consequently for the investigation of the properties of the air masses which may appear in a given locality, the most significant designation of the different individual polar and tropical air mass types is that based on the particular geographical area within which the air mass has its source. It is necessary to keep in mind the season of the year when considering the characteristics of any particular geographical source region, as these characteristics, especially in the case of the continental areas, change greatly from the cold to the warm season.

b. Table I gives the classification of North American air masses. The last column shows how these air masses fit into the general classification of Bergeron. The principal source air masses in Bergeron's classification are the continental Polar (cP), maritime Polar (mP), and so on for cT and mT. This manner of designation has been adopted by the United States Weather Bureau. Modification of the source properties of the air mass, which is indicated by an N or numbered subscripts in the Air Corps, is indicated by a W (warm) or a

K (cold, from the German "kalt"). The warm (W) designation indicates that the air mass is warm relative to the surface it is moving over, the cold (K) indicates that it is cold relative to the surface it is moving over. Thus, cPW indicates cP (continental Polar) air that has left its source region and is warmer than the surface over which it is moving. This warm and cold designation has nothing to do with the evidence by the air mass of a high or low temperature, but only as to the evidence of a temperature near the surface higher or lower than that of the surface beneath. The passage of the air mass from ocean to continent or the transition from day to night may reverse the sign of the difference of the air temperature from that of the surface beneath.

c. A polar air mass may act like a warm air mass. This may be both in relation to the surface being passed over and to another polar mass which is colder. It is the relative value of temperature and not the absolute value that counts in the determination of whether an air mass is going to act like a cold or a warm one.

52. Air mass properties.—*a*. *General.*—(1) The important air mass properties used to identify air masses, determine their structure, and locate fronts are—

Temperature.
Relative humidity.
Specific humidity.
Dew point.
Potential temperature.
Equivalent potential temperature.
Stability.
Ceiling.
Visibility.
Clouds.
Precipitation.

(2) From the standpoint of the pilot, the ones that have the most practical use are—

Temperature.
Dew point.
Ceiling.
Visibility.
Clouds.
Precipitation.

Ceiling and visibility are usually the deciding factors. However, all of the properties have interrelations and it may be any one or any combination that causes a ceiling to come down. Precipitation affects both the ceiling and visibility. The types of precipitation, whether liquid or solid, are known as "hydrometeors." Clouds and hydrometeors are the only elements that give a visible indication of thermodynamic processes in the atmosphere and hence are of vast importance in air mass analysis.

(3) The classification of hydrometeors based mainly on their appearance is as follows:

(*a*) *Rain* is precipitation consisting of drops of water greater than ½ mm in diameter.

(*b*) *Drizzle* consists of small liquid droplets that seem to fill the air yet they can only be seen with difficulty. Drizzle comes from fog or stratus clouds. Fog with drizzle means the presence of a warm air mass. It is important to distinguish drizzle from rain, especially in regard to the location of fronts. Drizzle may occur far from the frontal zones but rain usually means that a front is present. The size of the droplet is important since the larger the drop, the higher the ceiling.

(*c*) *Snow* is hexagonal or star ice crystals.

(*d*) *Sleet* is frozen rain. It should be remembered that snow that melts on the way down will appear as rain but rain that freezes on the way down will not appear as snow.

(*e*) *Granular snow* is elastic; it rebounds when it hits the ground and breaks when it hits a hard object. It occurs near 0° C. and is usually a sign of instability.

(*f*) *Freezing rain* is rain that instantly freezes to objects it strikes.

(*g*) *Mist* is composed of small droplets that do not make wet spots over 1/16 inch in diameter. It often resembles fog but is identified by the occurrence of drops of a size appreciable to the face or hands.

(*h*) *Freezing mist* is mist that instantly freezes to objects it strikes in the open.

(*i*) *Soft hail* is precipitation of opaque grains (diameter 1 to 5 mm). They are crisp and bounce off the ground and disintegrate readily. They sometimes consist of a core of snow surrounded by a crust of opaque ice. They often fall with rain.

(*j*) *Hail* is precipitation of round or irregular lumps of solid and fairly transparent ice. They occur almost exclusively in thundery weather and are rare in high altitudes.

(4) The processes leading to the formation of hydrometeors are mainly of three kinds:

(*a*) More or less continuous precipitation from continuous cloud cover (altostratus and nimbostratus), or precipitation caused by slow upward movement of a large mass of air due to convergence in the horizontal motion of the air (frontal precipitation).

(*b*) Showers, or precipitation of short duration that begins and ends suddenly, usually with fair periods between. This kind of precipitation, which originates in cumuliform clouds, is caused by the fairly rapid rising of small bodies of air through the atmosphere (instability precipitation).

(*c*) Drizzle, or numerous small droplets falling from fog or stratus.

This kind of precipitation is not connected with any appreciable ascensional velocity; on the contrary, the small drops fall out of the cloud because of the absence of any appreciable upward movement.

b. Cold air mass.—(1) A cold air mass is an air mass which is colder than the surface over which it travels. The source regions are either polar or arctic areas. In winter, the source region for cold masses may extend down over snow-covered continents to 20° or 30° latitude. The result is that a cold mass may have largely varying properties. Polar masses are distinguished by—

(*a*) Stable stratification, notably in the lower layers.

(*b*) Low specific humidity.

(*c*) Low temperatures.

(2) When such a mass moves toward warmer regions, it will always be colder than the surface over which it is moving. The mass will be heated from below and thermal instability will soon develop in the lower layers and gradually spread upward. If the air originally contained inversions, these will be destroyed by continued heating from below with the result that uniform steep lapse rates develop throughout the mass; this results in convective currents.

(3) If the cold mass travels over water, it will pick up moisture which is brought up to higher and higher levels by the convective currents. Convective clouds form and soon develop into cumulonimbus. If the cold mass travels over land, it will be heated from below but will not absorb much moisture. In this case, convective clouds do not easily form until the instability has reached up to very great heights. Therefore, continental cold masses are often cloudless.

(4) Pc air in winter moves only a few miles off the coast of Alaska before it develops showers or snow squalls. Pp air that moves rapidly southward over the Pacific Ocean soon develops showers, while the Pc that comes down over the Great Plains may be cloudless.

(5) The upper stable layers of a cold mass frequently limit the growth of cumulus clouds. It is only when no such limiting levels are reached that a cumulus cloud attains its full growth and the true characteristics of cumulus clouds in a cold mass may be displayed. The strongest limiting factor is a temperature inversion and cumulus clouds rarely penetrate such a layer. Flat-topped cumulus clouds indicate stable layers aloft whereas towering cumulus indicate instability aloft.

(6) Polar maritime masses as they move over warmer water surfaces are characterized by—

(*a*) Increasing temperature.

(*b*) Increasing potential temperature.

(c) Increasing specific humidity because of absorption of moisture from below.

(d) Increasing equivalent potential temperature.

(e) Instability in the lower levels.

(f) Increasing turbulence and gustiness.

(g) Cumuliform clouds and showery precipitation.

(h) The look of the sky continually changing from dark to light portions.

(i) Rapidly drifting clouds.

(j) An increase of cloudiness at night and early morning.

(k) Small diurnal variation in temperature.

(l) Good visibility.

(m) Ceilings usually more than 1,000 feet.

(7) Polar continental masses as they move over warmer land surfaces are characterized by—

(a) Increasing temperature, potential temperature, and equivalent potential temperature.

(b) Slight increase of specific humidity.

(c) Instability in the lower levels.

(d) Increasing turbulence and gustiness.

(e) Scattered cumuliform clouds, occasional showers or snow flurries.

(f) Increasing cloudiness during the day and minimum cloudiness at night, maximum in the afternoon.

(g) Small diurnal variation in temperature.

(h) Good visibility except when restricted by dust or smoke.

(i) Ceilings usually more than 1,500 feet.

(8) When a polar continental mass moves over the ocean in winter, it rapidly becomes unstable and forms cumuliform clouds with showers and squalls. If it moves over the ocean in summer, it becomes more stable.

(9) When a polar maritime mass moves over land in winter, it rapidly becomes stable, the clouds change from the cumuliform to the stratiform type, and the showers gradually decrease to become nonexistent. When this mass moves over land in summer, it becomes more unstable. However, the instability is not usually sufficient to cause showers.

(10) The exception to typical cold mass characteristics are chiefly the clearing and the development of stability caused by subsidence, the effects of topography such as adiabatic heating with clearing on the leeward side of mountains, and the possibility that the top of the unstable layer does not reach up to the saturation level and hence no clouds.

c. Warm air mass.—(1) The source regions of warm air masses are usually the oceanic areas in the subtropical high-pressure belt. Warm air masses that frequent the United States are rarely of continental origin although they may sometimes originate in summer over the southern portions of North America. Warm maritime air masses are characterized by—

(*a*) High temperatures.

(*b*) High specific humidity.

(*c*) A lapse rate that is less than 6° C/km.

(2) Warm continental masses are similar in their characteristics except that the temperature is a little higher and the specific humidity is a little lower.

(3) Tropical maritime masses as they move over colder regions are stabilized in the lower levels because of the cooling from below. This cooling creates an inversion which suppresses turbulence and prevents convections. Therefore, the upper levels are not materially altered. These air masses are characterized by—

(*a*) Conservative temperatures at high altitudes.

(*b*) Stable lapse rate, with an inversion in the lower levels.

(*c*) Little turbulence and gustiness.

(*d*) Poor visibility due to fog, drizzle, and haze.

(*e*) Stratiform clouds with fog and low stratus frequent.

(*f*) Precipitation in form of drizzle.

(*g*) Large diurnal temperature variation.

(*h*) Maximum cloudiness in the early morning and minimum in the afternoon.

(4) As the warm, moist air is continually cooled from below, it is brought close to its saturation temperature or dew point. Frequently they become the same and fog forms. Strong winds or insolation after sunrise may be sufficient to lift the fog to low stratus.

(5) When tropical maritime air masses move over land in summer, instability develops because the land is warmer than the air during the day. Scattered showers and thunderstorms result, especially if there is a little convergence along a weak front. At night, the air is warmer than the land but is usually not cooled sufficiently to form fog and low stratus except in coastal areas.

(6) Tropical continental masses that develop in summer are conditionally unstable but their temperatures are so high that clouds rarely develop. The instability created during the day may cause turbulence to above 10,000 feet. These masses cause extreme heat waves.

53. Fields of motion.—The distribution of wind direction and

velocity over a given area constitutes the field of motion for that particular area. This distribution of wind velocity and direction is responsible for the position of fronts and waves. There are many local factors that influence the wind and unless these influences are taken into consideration, erroneous conclusions may result. In making a careful analysis, the chief problem of the forecaster is to determine the true winds as shown by the field of pressure because there is no local influence on pressure; that is, pressure reports are representative.

a. Effect of local influences on the wind.—In evaluating the reports of wind velocity and direction, the following factors should be taken into consideration:

(1) *Size and shape of obstacles.*—The anemometer should be located so that purely local obstructions do not exist. The most normal effect of local obstructions is to decrease the wind velocity. Large obstacles, such as mountains, cannot be moved and their effects must be considered. Wind reports in mountainous regions will not usually be representative below the general level of the mountain tops. Mountain ranges usually cause the wind to have a component parallel to the ranges.

(2) *Variation of winds with height.*—The wind attains its true velocity and direction as represented by the surface pressure field at about 2,000 feet above the surface. Above that height, winds may vary considerably in both velocity and direction because the strongest pressure gradients exist aloft. The pressure field at 10,000 feet may not even resemble the surface pressure field. In general, wind velocity increases with elevation and wind direction becomes more westerly with higher altitude. Figure 85 shows the average turning of the wind with elevation in the United States.

(3) *Stability of the air.*—Stable layers decrease the wind velocity and cause supernormal velocities in the adjacent layers. The wind approaches its true velocity in unstable air. Therefore wind direction and velocity is more reliable in a cold air mass than in a warm air mass.

(4) *Strength of the wind.*—Large wind velocities are usually representative. Light winds are usually nonrepresentative and are locally influenced.

(5) *Time of day.*—Surface winds on the night and early morning weather maps are usually not representative because of the stability of the air near the ground at night. Afternoon winds are the most representative because of the turbulence and instability set up by diurnal heating. Winds over the ocean are fairly representative day and night.

(6) *Stability in relation to mountains.*—An unstable air mass is retarded but easily gets over a mountain range. A stable air mass has great difficulty in getting over a mountain range and tends to go around if possible.

b. Relation of wind to pressure.—(1) At about 2,000 feet above the surface, the wind blows along the surface isobars, counterclockwise in a cyclone and clockwise in an anticyclone, with a velocity that is inversely proportional to the distance between isobars; that is, the closer together the isobars, the stronger the wind. It was also shown by the

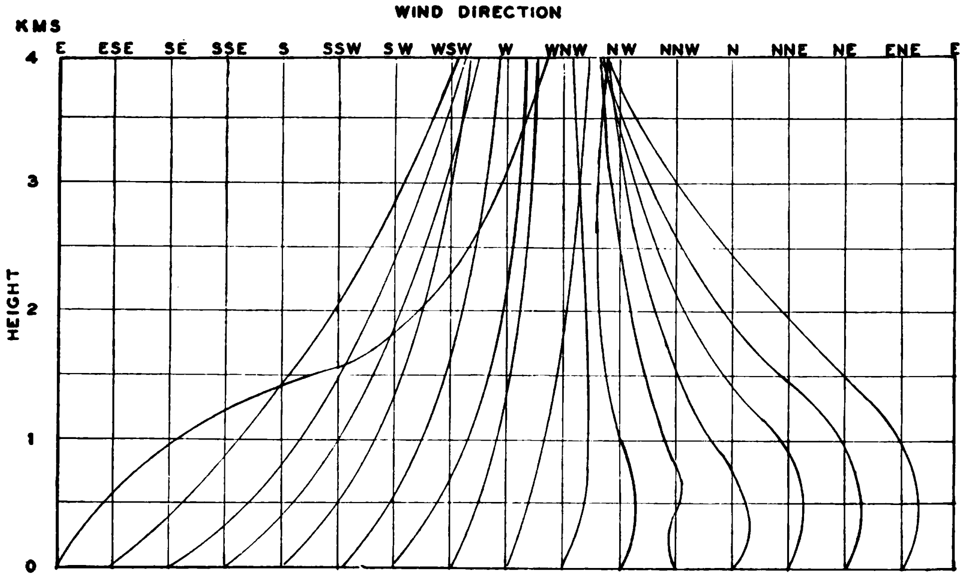


FIGURE 85.—Average annual turning of the winds with altitude in the United States.

geostrophic and gradient wind equations that there is a fixed wind velocity for each distance between isobars for any given latitude. Nearer the surface than 2,000 feet, these winds are deflected to the left by the effects of surface friction (observer standing with his back to the wind; that is, looking down wind).

(2) These relations hold true for a pressure field in which no changes are occurring. In nature, the pressure field is normally undergoing changes; the isobars and associated pressure systems are moving. The change of pressure during a 3-hour period at a fixed station is called the "barometric tendency." Lines that connect points of equal tendency are called "isallobars." There are isallobaric gradients and isallobaric ascendants just as there are pressure gradients and pressure ascendants. The isallobaric gradient is the line along which there is the most rapid rate of decrease of barometric tendency. The isallobaric ascendant is the line along which there is the most rapid rate of increase of tendency. The direction and velocity of the

wind is affected by the movement of pressure systems. The true wind consists of two parts, a geostrophic component and an isallobaric component. The direction of the wind is between the isallobaric gradient and the isobars. The larger the isallobaric gradient, the more the wind is deflected toward lower pressure; that is, when pressure systems move rapidly, they tend to overcome the effect of the earth's rotation and the wind blows more directly from higher to lower pressure. This phenomenon frequently takes place when cold waves move rapidly southward; the winds may blow almost directly across the isobars. Two rules may be derived from the above:

(*a*) Accelerated winds have a large angle between the true wind and the isobars.

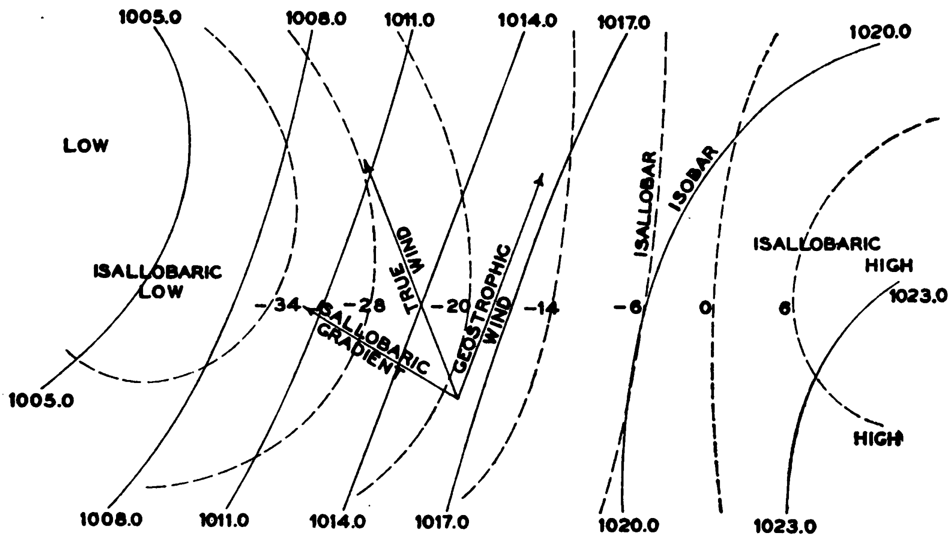


FIGURE 86.—Effect of isallobaric gradient on winds.

(*b*) Nonaccelerated winds have a small angle between the true wind and the isobars.

(3) Whenever the isallobaric gradients are pronounced, there will be up glide, increasing with height, in an area of converging isallobaric gradients, and there will be subsidence, increasing with height, in an area where the isallobaric gradients diverge.

c. *Frontogenesis and frontolysis.*—Fronts form, and when formed they are subject to processes that either strengthen or weaken them. Frontogenesis is the process by which fronts are formed and strengthened. Frontolysis is the process by which fronts are dissolved. There are numerous processes that aid frontolysis but few that aid frontogenesis. Fronts are zones of transition in air mass properties. These zones of transition are of the order of 10 kilometers in width and therefore appear on the weather map as lines. Theo-

retically, there are two means by which fronts might be formed; physical and kinematic (movement).

(1) A *physical process* for the formation of fronts would require a hot area adjacent to a cold area. This is not the main process of front formation because, if so, fronts could only form along a radiation discontinuity and the air must be stagnant. Weak fronts of this type sometimes tend to form along coast lines but they are not of synoptic importance.

(2) The *kinematic process* produces fronts. When air masses are brought from distant sources of different types, the meeting of

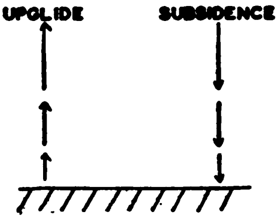


FIGURE 87.—Effect of isallobaric convergence and divergence.

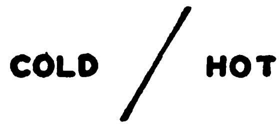


FIGURE 88.—Radiation front.

different types produces fronts. In this case, there is really a transport of properties from one place to another. Air mass properties are transported by the wind.

d. Types of motion.—The equations of motion for a linear field of motion are—

$$u = u_0 + ax + bx - cy$$
$$v = v_0 - ay + by + cx$$

where u and v are the components along the x and y axes, u_0 and v_0 are the initial components in those directions, and a, b, and c represent any numerical coefficients. These equations may be extended to include w and z terms to take care of motions in the third dimension but these will not be considered here. The six basic types of motion, translation, deformation, divergence, cyclonic rotation, convergence, and anticyclonic rotation, and how they are derived are shown in figure 89.

(1) Pure translation can produce neither frontogenesis nor frontolysis.

(2) Divergence causes frontolysis.

(3) Convergence causes frontogenesis.

(4) Pure rotation of either type cannot cause either frontogenesis or frontolysis.

(5) Deformation can produce either frontogenesis or frontolysis.

(*a*) In considering the deformation field of motion, it will be shown how this field may cause widely varying properties to be concentrated

along a narrow zone and how it may cause fairly uniform properties to be distributed over a wide area. A line, along which the value of any given property is constant, is called an "isoline of property."

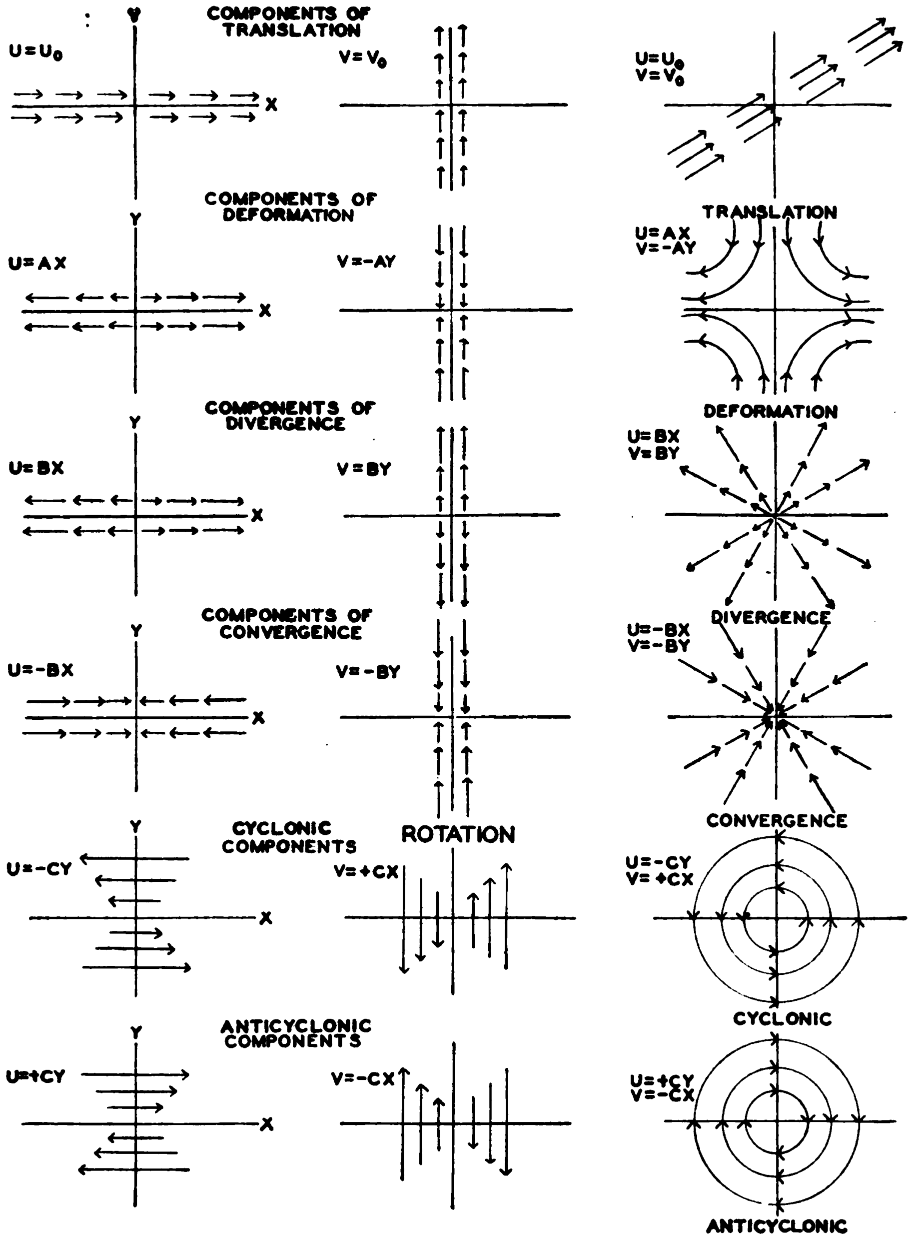


FIGURE 89.—The basic fields of motion.

An "isotherm" is a line along which the temperature is constant and is, therefore, an isoline of property. The axis of outflow in a deformation field of motion is the "dilatation axis"; the axis of inflow is the "contraction axis." When the isolines of property in a deformation

field are roughly parallel to the dilatation axis, frontogenesis takes place. Consideration of figure 90 will show that if the indicated motions are allowed to continue, the isotherms will be stacked along the dilatation axis with the 60° isotherm near the 10° isotherm. A rapid zone of transition of property, a front, will be produced. It is by such fields of motion tht the warm tropical masses are brought in contact with the cold polar masses and the polar front is formed. Fronts other than the polar front are created by similar means.

(*b*) When the isolines of property are oriented roughly parallel to the contraction axis, as shown in figure 90, further motion will spread

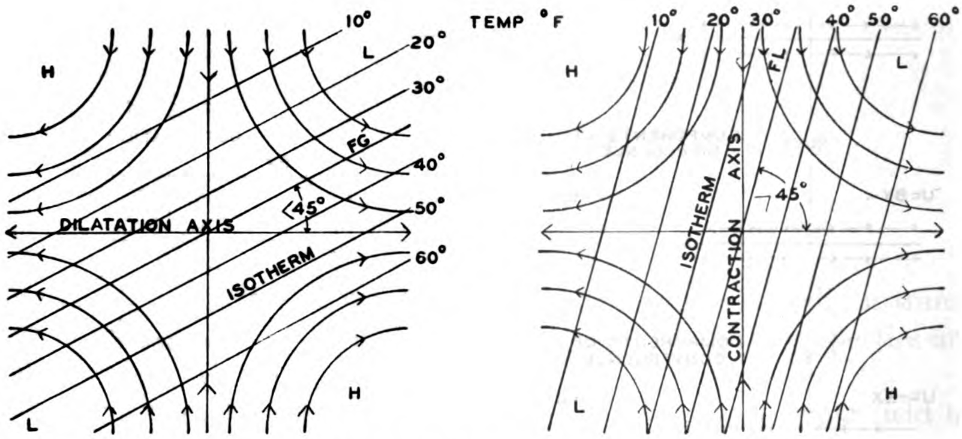


FIGURE 90.—Frontogenesis. Frontolysis.

them far apart and distribute uniform properties over a wide area, producing frontolysis. The critical angle is 45°.

(6) Since the effect of friction is to deflect surface winds to the left, a cyclone in nature represents a combination of cyclonic rotation and convergence. As a result, frontogenesis is continually taking place in a cyclone. As the wind spirals in toward the center, an excess of air accumulates within the central portion of a cyclone, so it goes up since it cannot go into the surface. This accounts for the large areas of low clouds associated with a moist cyclone. Figure 91 shows a plan of a cyclone with isobars and vectors representing the wind. Figure 92 shows a similar plan for an anticyclone. Surface friction, as shown in this diagram, deflects the winds away from the center which gives a combination of anticyclonic rotation and divergence with resultant frontolysis. The subsidence that must occur in an anticyclone, due to the outward distribution of the air in the lower levels, causes the descending air to be heated adiabatically. This reduces the relative humidity and decreases the opportunity for the formation of clouds.

(7) From the surface motions in highs and lows, forecasters in the past have been led to believe that there should always be good weather in high pressure areas and bad weather in low pressure areas. When observations frequently did not bear out these ideas, the weather man was sorely puzzled. He did not then realize the existence of air masses and fronts and their interactions. Also, he did not have the upper air data that are available today. The theory of frontogenesis was developed by Bergeron and extended by Petterssen.

54. Properties common to all fronts.—In the location of fronts on the weather map as well as from radio weather reports, the best thing to use is barometric pressure, while the easiest to use is the wind.

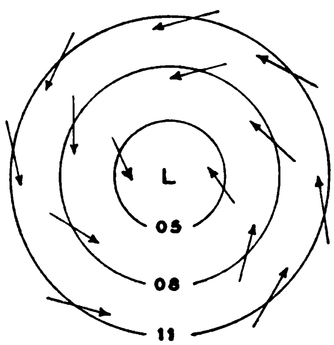


FIGURE 91.—Frontogenesis in a cyclone.

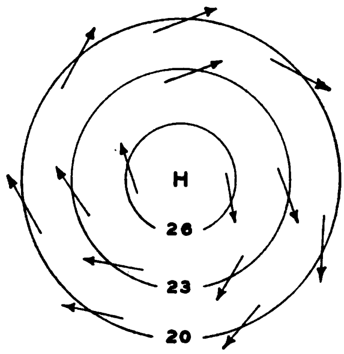


FIGURE 92.—Frontolysis in an anticyclone.

These elements have certain relations which must hold true for all fronts. Some of these are listed below.

a. The pressure gradient is discontinuous at a front; that is, the spacing and orientation of the isobars are never exactly the same on both sides of a front (fig. 93).

b. The pressure is continuous at a front. This condition originates from the principle of equal action and reaction. It means that isobars never break at a front (fig. 93).

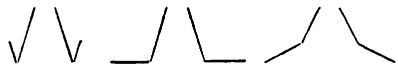
c. There must be a V in the isobars at a front. This V is frequently called a "hook," and it must be oriented so that it points away from lower pressure. This follows from *a* and *b* above (fig. 93).

d. A front must lie in a pressure trough. This follows from *c* above. A "pressure trough" is an elongated area, extending from a low center, in which the pressure is lower than on either side (fig. 93).

e. There must be cyclonic curl along every front. The winds in the vicinity of a front must have the same type of motion as in a cyclone, that is, counterclockwise. The location of a front may easily be tested by this rule if the network of reporting stations is dense (fig. 93).

f. There must be a hook in the pressure tendency characteristic if a

front has passed a station during the past 3 hours. This rule is not



entirely reliable for tendencies of less than −6 because of possible errors due to local oscillations such as slamming of doors, improper reading and reporting.

g. There is a wind shift at the front since the winds follow the isobars. When a front passes a station, the wind shifts in a clockwise

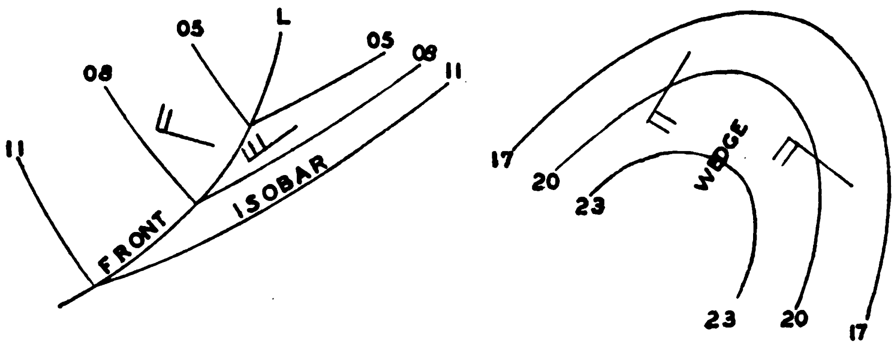


FIGURE 93.—Front present. No front possible.

direction, for example, from E. to S., from S. to SW., or from SW. to NW. (fig. 93).

h. There are no hooks in the tendency if the front is stationary.

i. There is a line of convergence in the field of flow.

j. A front must be an inclined surface with warmer air above an underlying wedge of colder air. An overhanging cold front rarely exists.

A rapidly moving cold front may overhang due to the retardation of the surface front by surface friction. An example of this occurred

FIGURE 94.—Normal relation. Overhanging cold front.

at Dallas, Texas, when a cold front that was rapidly moving southward carried dust with it. The frontal surface was visibly marked by the forward boundary of the dust which appeared like a black cloud moving over the city while the city itself was still in clear air. The ceiling and visibility in the dust were zero and it was only a few minutes after the dark cloud appeared over the city, until the entire district was plunged into darkness.

55. Moist and dry fronts.—*a.* One of the first things a student notes in looking at a weather map is that some fronts are more active

than others; that is, the clouds and precipitation are more widespread in one than in the other and the "bad" weather continues for a longer period. In order to understand why that is so, a brief explanation of the reason for the varying amounts of activity is given. The extent of activity which is noted on a weather map is actually dependent upon the amount of energy which each front possesses. Potential energy is latent energy or energy not realized, while kinetic energy results when the potential energy is released.

b. The release of potential energy or the transformation of potential energy to kinetic energy is the result of an attempt by the earth's atmosphere to reestablish equilibrium. Equilibrium in the atmosphere will exist when particles at the same level throughout the atmosphere have the same temperature. Therefore, the greater the temperature contrast between air masses, the greater is the movement necessary to establish equilibrium; or, the greater the contrast, the more available potential energy, and the more kinetic energy to be created.

c. Each front or surface of discontinuity has associated with it a cyclone. The activity of the front and the frontal cyclone is dependent on the kinetic energy of the air movements and the release of the potential energy of the two air masses. One of the most important sources of the potential energy is the moisture content of the air masses involved. For this reason frontal cyclones and fronts may be subdivided into moist and dry systems which are discussed in sections IX and X. Several pertinent facts about moist and dry cyclones which will be very helpful to the pilot are given below:

(1) Since there is more moisture in moist cyclones, there is more potential energy and therefore more time is required to release this energy. A dry cyclone occludes more rapidly and dissipates sooner than a moist cyclone.

(2) The frequency of the dry cyclone, or period between waves, is less than in moist cyclones. That is, if the crest of a wave on a moist front passes an island in the Pacific Ocean at 12 o'clock on one day, the next crest would pass at 12 o'clock the next day. Whereas, in the Middle West, the time between crests may be 12 hours. The first example is a moist front, the second a dry front.

(3) Since more moisture means more energy, a cyclone moving offshore will frequently become more intense and thus more active.

d. The amount of moisture in either or both of the air masses connected with a front will determine the amount of activity that will result. Therefore, a logical division of fronts would be moist fronts and dry fronts.

56. Cold fronts.—The most marked weather changes take place along cold fronts and some of the most hazardous flying weather is found in cold front zones. A "squall line" was the name early given to what is now recognized as an active cold front. This term is still in good use and signifies a belt along which there is heavy rain or snow, low ceilings and visibilities, severe turbulence, often icing conditions, and frequent thunderstorms. The strong cold fronts are usually oriented in a NE. and SW. direction and move SE. They are followed by cooler and drier weather often preceding severe cold spells and sometimes dust storms. Their rate of motion is 80 to 100 percent of the velocity of the component of the geostrophic wind in the direction of motion of the front. New cyclones mostly form at the cold front in the SW. sector of an old cyclone. There are two general types of cold fronts; slowly moving or retarded, and rapidly

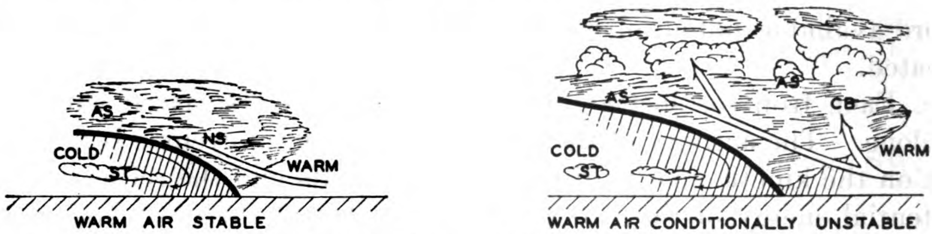


FIGURE 95.—Vertical sections across slowly moving cold fronts.

moving. These types often change gradually from one to the other so that any differentiation during the intermediate stages must be arbitrary.

a. Slowly moving or retarded cold fronts.—(1) There is a general upsliding motion of the warm air along the frontal surface (fig. 94) and formation of a rather broad post-frontal altostratus and nimbostratus cloud system in the warm air when it is stable. Stratiform clouds may form in the warm air several miles ahead of the surface front. If the warm air is conditionally unstable, cumulonimbus clouds and frequently thunderstorms develop within the thick stratiform cloud system of the stable case. There may be enough upward movement in the cold air to form low stratiform clouds.

(2) The determination of the stability, ice crystal level, and level of free convection of the warm air is important because the wedge of cold air may not be thick enough to lift the stratiform clouds to the rain-forming level or high enough to allow the instability of potentially unstable warm air to be released. The stability of the air may be determined from soundings or the type of clouds present. All towering cumuliform clouds indicate instability.

b. Fast moving cold fronts.—The motions in this cold front combine

downward movement above and below the frontal surface with upward movement in the warm air ahead of the front as shown in figure 96. This is the most important type of cold front, is easily located on the weather map, and causes very hazardous weather. The main features of a fast moving cold front are as follows:

(1) Cloud systems that may extend more than 100 miles ahead of the front.

(2) Rapid clearing after the frontal passage.

(3) Tendency to dissolve near the ground.

(4) Overcast in a large area ahead of the front with a general rain when the warm air is stable.

(5) An almost continuous line of thunderstorms along the front and scattered thunderstorms and showers ahead of the front when the warm air is conditionally unstable.

(6) Frequent formation of a secondary cold front. The cold air near the front is heated by adiabatic descent and the warmer ground.

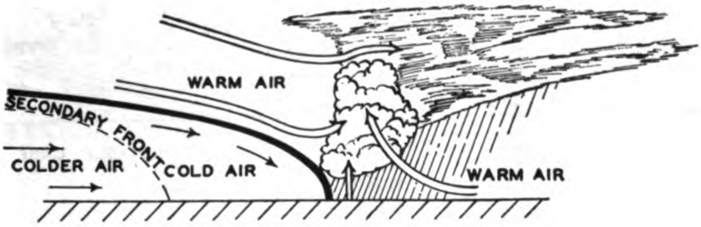


FIGURE 96.—Fast moving cold front.

Frontogenesis sharpens the secondary front in about 40 percent of the cases of rapidly moving cold fronts and brings the fronts together again by causing the secondary front to catch up with the retarded primary front. This process may be repeated.

(7) Gusty, turbulent surface winds behind the front.

(8) A steep frontal edge in contrast to the slowly moving cold fronts which have a relatively flat frontal edge.

57. Warm fronts.—*a.* A front along which warmer air is replacing colder air is called a "warm front." Warm front slopes are of the order of 1/50 to 1/200 with an average value of about 1/100. A rise of 5,280 feet over a distance of 100 miles is a very gentle slope. This fact may be used to advantage by pilots seeking the best tail wind since the winds above and below the frontal surface usually vary considerably.

b. The air from the warm sector, as shown in figure 97, gradually moves up over the sloping warm front surface and forms a broad prefrontal cloud system of stratiform clouds if the air is stable and of both stratiform and cumuliform clouds if the warm air is potentially

unstable. The sequence of cloud types from the warm sector out over the frontal surface to clear air is nimbostratus, altostratus, cirrostratus, and cirrus. If the air is conditionally unstable, cumulonimbus and altocumulus clouds and frequently thunderstorms will be scattered ahead of the warm front. The precipitation that falls from the cloud system usually starts gradually and increases, then continues evenly until the passage of the system. When cumulonimbus clouds develop, the even warm front precipitation will become spotty in character with much heavier rain or snow in scattered areas beneath the cumuliform clouds.

c. Warm fronts generally move to the northeast with a velocity of about 60 to 80 percent of the component of the geostrophic wind in the direction of motion. Their speed is usually a little above half that of cold fronts and they usually are not as well marked as the cold fronts because the warm rain heats and moistens the cold air through which it is falling. The physical characteristics of a cold air mass

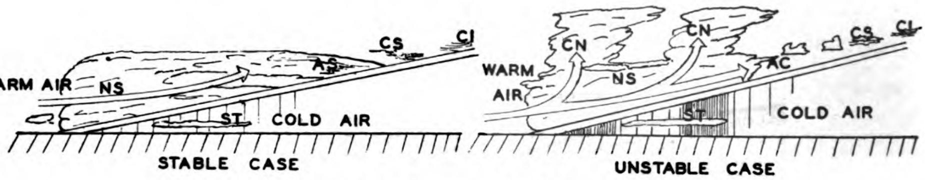


FIGURE 97.—Warm front cloud systems.

may be altered a great deal in a comparatively short time through the modifying effect of a warm front rain.

d. The wide precipitation area ahead of a warm front often contributes to serious aviation hazards in the form of very low ceilings and visibilities. The humidity of the cold air is raised to near saturation by the rain and after the sun sets additional cooling plus the pressure drop ahead of the approaching center may cause fog in thousands of square miles. The frontal zone itself may cause zero ceilings and visibilities over a wide area.

e. Very cold air underneath a warm front is resistant to displacement and may force the warm air to move over a thinning wedge with waves in the upper surface. This gives the effect of secondary upper warm fronts and may cause parallel bands of precipitation at unusual distances ahead of the surface warm front. Some of these upper warm fronts may reach down to the surface and give two or more parallel warm fronts at the surface.

f. Secondary warm fronts are also formed by returning polar air that has had varying amounts of time over a warm surface such as the Gulf of Mexico. This type of air has a high degree of potential

instability and is quite dry aloft. Low ceilings and visibilities frequently occur along the weak fronts formed.

58. Stationary fronts.—Fronts that have little movement are called "stationary fronts." A front of this type may develop either into a cold or a warm front but more resembles a warm front. A cold front that slows down will usually change its characteristics to those similar to a warm front. Real stationary fronts are very rare and fronts with no movement do not exist. Detailed studies, conducted with the aid of a dense network of anemometers and thermographs, have shown that fronts which appear to be stationary on small scale synoptic weather maps, actually are undergoing continual movement, chiefly in the form of minor waves with extremely variable wave lengths and amplitudes. It was also found that other types of fronts contained similar irregularities. Therefore it is concluded that a forecast of the time of arrival of a front from a linear extrapolation of its previous rate of progress is very apt to contain significant error.

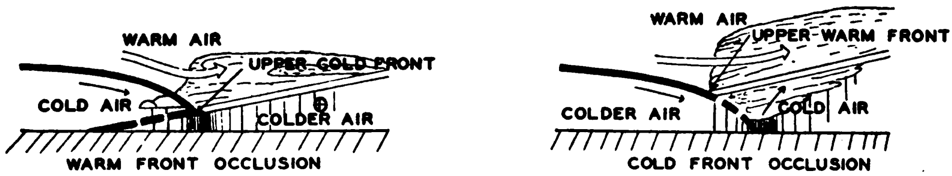


FIGURE 98.—Types of occlusions.

Islands of warm or cold air are sometimes trapped by the irregularities in cold or warm fronts, respectively.

59. Occluded fronts.—*a.* The front that occurs when the cold front overtakes the warm front in a wave is called an "occluded front." There are two types of occluded fronts; warm front occlusions and cold front occlusions as illustrated in figure 98. When the air behind the cold front is warmer than the air ahead of the warm front a warm type occlusion occurs, and when the air behind the cold front is colder than the air ahead of the warm front a cold front type occlusion occurs. The latter type is much more common.

b. When a cold front occlusion from the Pacific Ocean moves onshore in western Canada, the air behind the occlusion is frequently warmer than the cold continental air ahead of it, so the occlusion changes from the cold front type to the warm front type. The upper fronts usually dissolve and leave the surface front similar to either a cold front or a warm front.

c. The occlusion process is nature's attempt to establish equilibrium by distributing the cold air everywhere underneath the warm air.

60. Upper fronts.—*a.* An upper front is a front that exists at high levels, with which the phenomena accompanying exist only aloft.

One method of formation of upper fronts is by means of the occlusion process as shown in figure 98. Another method was described in paragraph 54. A surface cold front may go aloft when it strikes colder air ahead and form an upper cold front. This frequently happens when a Pp cold front strikes Pc air; also Pp cold fronts that have had a trajectory over the southwestern United States in

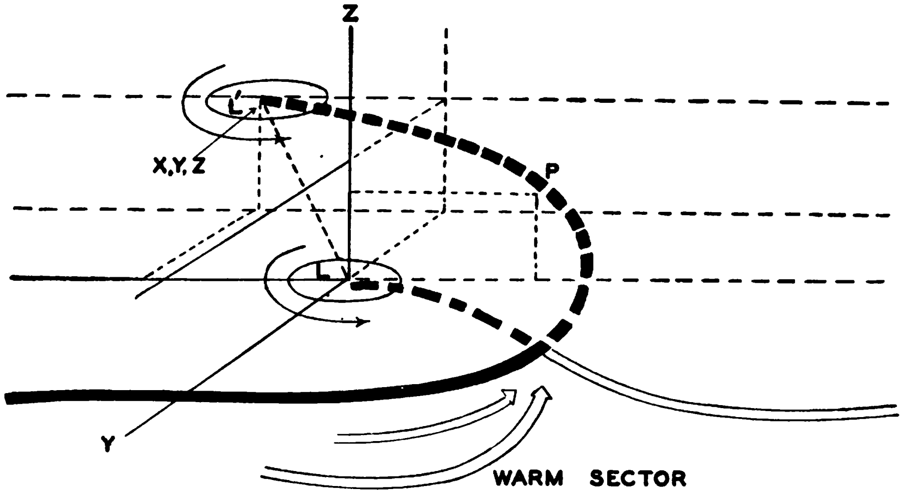


FIGURE 99.—A three-dimensional picture of the warm front occlusion. (L=low pressure center at the ground; L′=low pressure center in the warm air aloft; P=the point where the upper cold front pierces the x–z plane).

the spring and fall sometimes overrun Tg air. Convergence aloft may form an upper front.

b. Upper fronts are difficult to find on the surface weather map. Upper air data are necessary in order to locate them. Soundings are most desirable but their present sparse network and infrequency make the winds aloft the best source of information. Upper fronts are sometimes masked by surface effects such as a thin monsoon or a sea breeze. They are particularly important in thunderstorm forecasting.

SECTION VII

NORTH AMERICAN WINTER AIR MASSES

Paragraph

61. General.—*a*. In winter, the Northern Hemisphere is inclined away from the sun. The more northerly latitudes experience little or no sunlight, while the middle latitudes suffer a marked reduction in the amount of insolational heating received. The land surfaces become very cold, ranging from −50° C. (−58° F.) in Canada to 0° C. in the Middle West. The ocean surfaces become only a few degrees colder than in summer.

(1) During the winter, land surfaces are much colder than water surfaces. All maritime air usually tends to become stable over land.

(2) Polar Continental air tends to become unstable over water.

(3) Cloud forms are cumuliform in polar maritime masses.

(4) Cloud forms are stratiform in tropical maritime masses.

b. Table VIII has been drawn up to give the principal characteristics of the air masses in winter. It should be understood that any statement concerning the various weather phenomena associated with any air mass must be a generality and exceptions will often be found.

62. Polar continental (Pc).—*a*. *Source region.*—The most important air mass affecting the North American Continent in winter is the Polar Continental air mass. The source of this air is the North American Continent north of the 50th parallel, from Hudson Bay to Alaska, and as far north as the Arctic regions. This region in winter is snow and ice covered, with long nights and short days. It is bounded on the west by the Canadian Rockies which tend to restrain the movement of air from the continent to the Pacific Ocean and from the Pacific to the interior of Canada. A stagnation of air over this region will result in the formation of large, very dry, cold bodies of air.

(1) *Temperature.*—The air is very cold, with temperatures ranging from 25° to 50° below 0° C. (−13° F. to −58° F.).

(2) *Moisture content.*—Values of specific humidity or "q" are less than 1 g/kg. Due to the low temperatures, the capacity of the air for moisture is low and the relative humidity high. Values of the relative humidity at the surface are from 89 to 95 percent, decreasing aloft. Thus, a lift of only a few hundred meters will be required to bring the surface air to saturation.

(3) *Lapse rate.*—Polar Continental air shows a pronounced temperature inversion up to 3,000 or 4,000 feet, with an isothermal layer or decrease in temperature above the inversion. This very stable lapse rate is caused by several factors: the reflection of solar radiation by the snow-covered surface, cooling during the long Arctic nights, and the short periods of sunlight.

TABLE VIII.—*The average properties and flying characteristics of those air masses occupying the United States in the winter*

Air masses	Temperature	Sp. humidity	Rel. humidity	Lapse rate	Cloud forms	Precipitation	Ceiling	Visibility	Turbulence	Icing
Pc in Middle West.	Surface −15° F. 4 km. −13.7° F.	Surface 0.32 g/kg. 4 km. 0.45g/kg.	Surface 85% 4 km. 45%	Very stable	Stratus and stratocumulus.	Light snow flurries.	1,000 to 2,000 feet.	Good	Only in lower levels.	Moderate rime
Pc with lake trajectory.	Surface 29° F. 1 km. 17° F.	Surface 2.6 g/kg. 1 km. 2.0 g/kg.	Surface 75% 1 km. 76%	Conditionally unstable in lower level.	Nimbostratus cumulonimbus.	Snow flurries	500 to 1,000 feet.	1–3 miles	Moderate below 4,000 feet.	Severe clear ice
Pp along west coast.	Surface 47° F. 4 km. −3° F.	Surface 5 g/kg 4 km. 0.4 g/kg	Surface 70% 4 km. 35%	Conditionally unstable.	Cumulus cumulonimbus.	Showers	1,000 to 3,000 feet.	Good	Moderate to severe.	East of coastal range.
Pp east of Rockies.	Surface 30° F. 1 km. 45° F.	Surface 3.0 g/kg. 1 km. 3.0 g/kg.	Surface 83% 1 km. 43%	Very stable	Clear	None	Unlimited	Unlimited	None	None.
Pa along east coast.	Surface 34° F. 4 km. −8° F.	Surface 3.0 g/kg. 4 km. 0.6 g/kg.	Surface 80% 4 km. 45%	Unstable in lower layer stable aloft.	Stratus stratocumulus.	Drizzle light rain.	500 to 800 feet.	1–3 miles	Moderate below 6,000 feet.	Clear ice lower levels.
Tg or Ta	Surface 65° F. 4 km. 36° F.	Surface 12.0 g/kg. 4 km. 1.5 g/kg.	Surface 80% 4 km. 35%	Conditionally unstable.	Stratus and stratocumulus.	Drizzle light rain.	500 to 1,500 feet at night.	1–5 miles	Light	None.
Tp	Surface 60° F. 4 km. 25° F.	Surface 8 g/kg. 4 km. 1.8 g/kg.	Surface 73% 4 km. 45%	Stable	Stratus	None	100 to 2,000 feet.	4–6 miles	None	None.

b. With land trajectory.—At frequent intervals during the winter, a part of this large mass of air will break off and move rapidly southward as a cold wave. As it moves away from its source region, the source properties change.

(1) *Factors changing source properties.*—(*a*) A modification due to supply of heat and moisture by contact with warm moist surface.

(*b*) A modification due to subsidence aloft. This intensifies the inversion and warms the upper levels.

(*c*) A modification due to turbulence. The rapid movement of air over irregular surfaces results in mixing the air.

(2) *Flying conditions.*—A pilot flying in a Pc air mass near the source region or in areas where the trajectory has been entirely over a land surface may expect to find the following conditions:

(*a*) Skies will be clear except in rapidly moving air over rough country, where turbulence will produce low stratocumulus clouds.

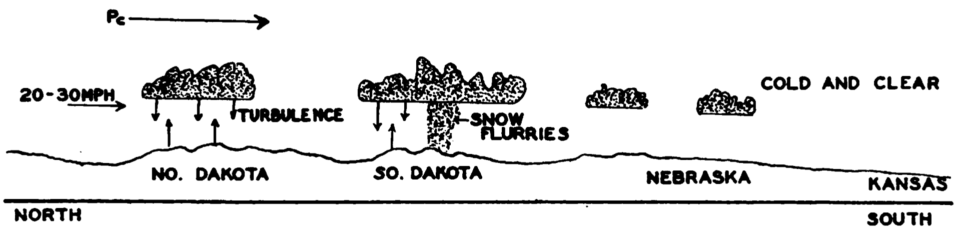


FIGURE 100.—Pc outbreak moving rapidly southward with land trajectory.

(*b*) Precipitation will be in the form of snow flurries and will occur only with high wind velocities.

(*c*) Visibilities will be excellent except in snow flurries.

(*d*) Due to stability of these masses, the air will be smooth except when wind velocities are very high. Ceilings will be unlimited. In the turbulent air, ceilings will be from 1,000 to 2,000 feet and less than 500 feet in precipitation.

(*e*) Due to the low temperatures and stability of the air, any icing will be of the rime type.

(*f*) With northeasterly or easterly winds, snow flurries with resulting low ceilings will be found along the eastward slope of the Rockies.

c. South of Great Lakes.—(1) *Modification of source properties.*—A good example of the modification of source properties occurs when Pc air crosses the Great Lakes.

(*a*) *Temperature.*—The temperature of the water being much more than that of the land, a sudden increase of temperature in the lower levels will result. This increase is often of the order of 8° to 10° C. (14° to 18° F.).

(*b*) *Moisture content.*—A corresponding increase in the moisture content will be noted. The specific humidity will increase from approximately 0.5 g/kg. to 2.0 g/kg.

(*c*) *Lapse rate.*—The increase of temperature and specific humidity will result in the formation of a convectively unstable layer from the surface to 1 to 2 kilometers.

(2) *Flying conditions.*—If a pilot is flying in a Pc air mass away from frontal zones, with northwest to northeast winds at lake shore stations, he may expect to find the following flying conditions south of the Great Lakes:

(*a*) Clouds are of instability type, stratocumulus and cumulus.

(*b*) Ceilings will be from 500 to 1,000 feet during the day and below 500 feet at night. Ceilings and visibilities will become very low in

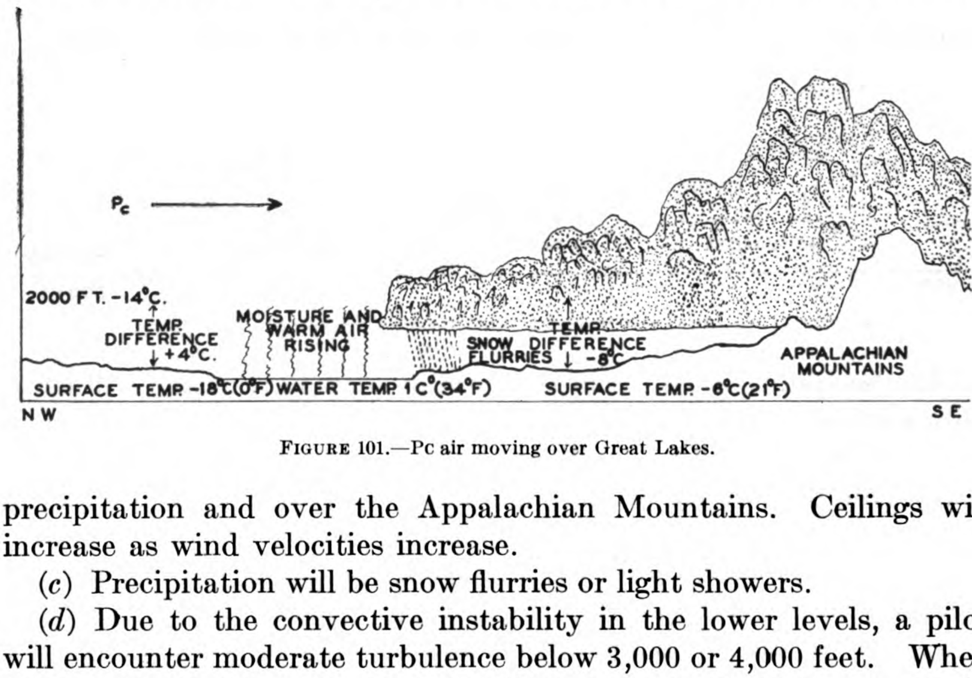


FIGURE 101.—Pc air moving over Great Lakes.

precipitation and over the Appalachian Mountains. Ceilings will increase as wind velocities increase.

(*c*) Precipitation will be snow flurries or light showers.

(*d*) Due to the convective instability in the lower levels, a pilot will encounter moderate turbulence below 3,000 or 4,000 feet. When the wind velocities are over 20 miles per hour, the turbulence will extend much higher. Over the Appalachians, the turbulence will be more pronounced.

(*e*) Clear ice will form readily in the lower levels in the Great Lakes region and at higher levels over the mountains.

d. With Gulf of Mexico trajectory.—(1) *Modification of source properties.*—As the Pc air moves southward and passes over the Gulf of Mexico, a very rapid modification takes place.

(*a*) *Temperature.*—After 36 to 48 hours over the Gulf of Mexico, the temperature will increase as much as 20° C. (36° F.).

(*b*) *Moisture content.*—The specific humidity increases to around 12 g/kg.

(*c*) *Lapse rate.*—The rapid addition of moisture and heat will cause the lower layers to become convectively unstable.

(2) *Flying conditions.*—A pilot flying along the southern and eastern coast will encounter conditions in this air similar to those found in Pc air south of the Great Lakes.

(*a*) Clouds will be cumulus or cumulonimbus.

(*b*) Precipitation will be of the showery type, intensifying as the pilot flies southward.

(*c*) Visibilities will range from 3 to 5 miles, becoming less than 1 mile in precipitation. Ceilings will range from 1,000 to 1,500 feet, becoming very low in the showers.

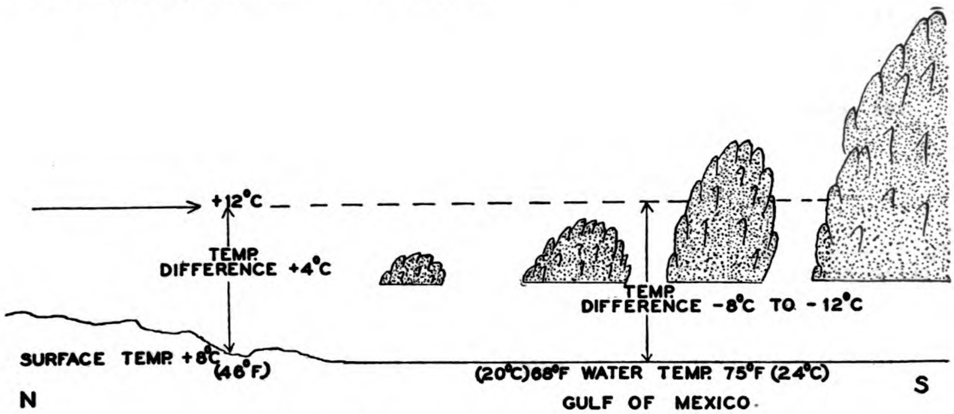


FIGURE 102.—Pc air mass moving over Gulf of Mexico.

(*d*) Turbulence will be moderate to severe, increasing toward the south.

(*e*) Clear ice will form in clouds above 6,000 feet.

e. With trajectory over Rockies.—The movements of Pc air westward over the Rocky Mountains and across the Great Basin is infrequent due to the stability of the air and the height of the mountains. Occasionally, Pc air moves southward from Canada parallel to the mountain ranges. In this case, the modifications are less marked and the northwestern States experience freezing temperatures.

(1) *Properties.*—The properties of Pc air when it reaches the Pacific coast have changed considerably.

(*a*) *Temperature.*—Adiabatic heating of the descending air will result in high temperatures.

(*b*) *Moisture content.*—The precipitation of moisture from the air as it moves over the mountains causes low humidities.

(*c*) *Lapse rate.*—As the air descends to the surface, the lapse rate becomes stabilized.

(2) *Flying conditions.*—Flying conditions will be very good with clear skies and unlimited visibilities.

f. With trajectory down Pacific coast.—Occasionally a low-pressure area off the coast of Washington will bring Pc air to the Pacific coast with only a day's travel over water.

(1) *Properties.*—The properties of this air will be very similar to those found in Pc air passing over the Great Lakes. Coldest weather along the California coast occurs in situations of this type. The convectively unstable air sometimes brings snow as far south as Los Angeles.

(2) *Flying conditions.*—The flying conditions are similar to those found in other Pc air masses after a water trajectory.

63. Polar Pacific (Pp).—*a. Source region.*—This air mass has as its source the ice-bound Arctic regions and the northern Pacific Ocean.

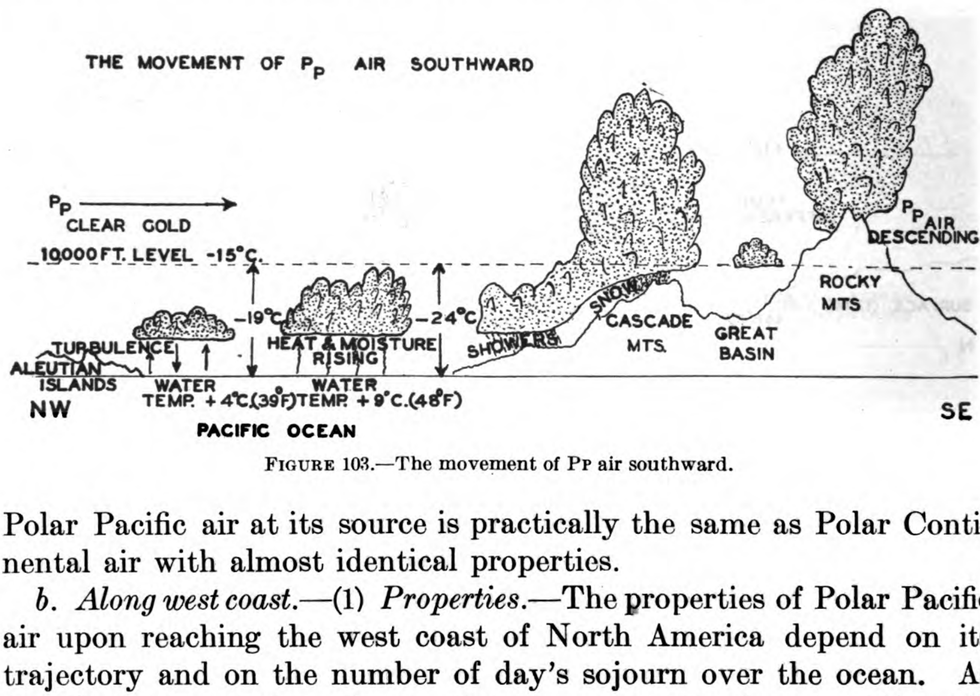


FIGURE 103.—The movement of Pp air southward.

Polar Pacific air at its source is practically the same as Polar Continental air with almost identical properties.

b. Along west coast.—(1) *Properties.*—The properties of Polar Pacific air upon reaching the west coast of North America depend on its trajectory and on the number of day's sojourn over the ocean. As the air moves southward over the warmer water, the properties will vary considerably. This variation and the height to which the modifications are distributed in the air depends upon the path followed. Above 4 kilometers the air remains similar to Polar Continental.

(*a*) *Temperature.*—The temperatures increase rapidly, averaging 8° C. (46° F.) at Seattle and 14° C. (57° F.) at San Diego.

(*b*) *Moisture content.*—A large increase of moisture in the lower levels is noted. The specific humidity becomes 4g/kg. at Seattle and

6g/kg. at San Diego, as compared to less than 1g/kg. in Pc air in south Canada.

(c) *Lapse rate.*—The rapid addition of heat and moisture from the ocean produces a conditionally unstable layer near the surface. The farther south the Pp air moves, the thicker the layer of conditionally unstable air becomes.

(2) *Flying conditions.*—Flying conditions in Polar Pacific air along the west coast will be characterized by the following type weather:

(a) Cloud forms are of the unstable type, cumulus and cumulonimbus.

(b) Precipitation due to the lifting of the convectively unstable air over the mountain ranges will be of the showery type. The precipi-

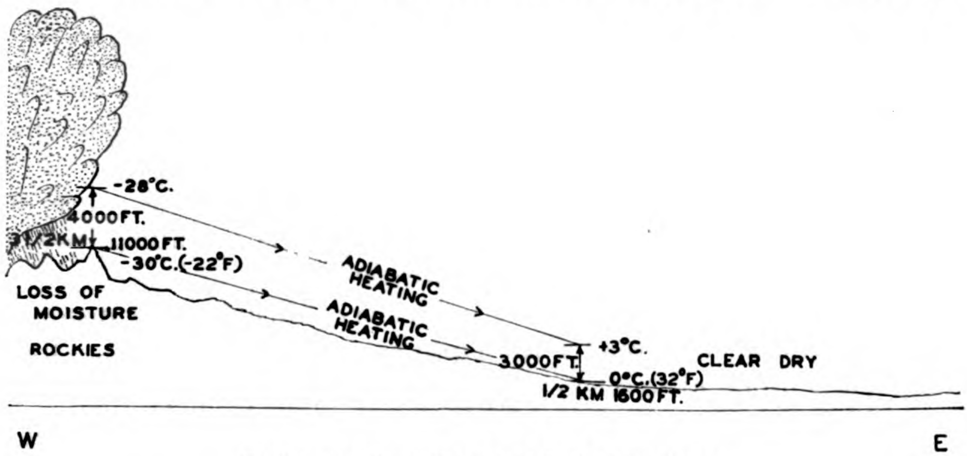


FIGURE 104.—Pp air descending Rocky Mountains.

tation will be light to moderate but usually not steady. Snow squalls will be found in higher mountains.

(c) Ceilings will be between 1,000 and 3,000 feet, except in showers, where they will be lower. Tops of clouds in mountains will extend to 15,000 feet. Visibility will be good, except decreasing to zero in showers.

(d) Turbulence will be moderate to severe, due to roughness of terrain and to instability of air. Above the clouds the air will be smooth.

(e) Icing conditions will be moderate to severe from the coast ranges eastward.

(f) Due to the passage over a cold surface and the mountains, and to loss of moisture through precipitation, the air becomes more stable, and after 24 hours over land the above flying condition becomes less severe.

c. *East of Rockies.*—Following the usual west-east trajectory of air masses in the middle latitudes, the Polar Pacific air moves eastward

across the mountain ranges. The lift caused by the coastal ranges releases the conditional instability, and heavy showers result. The showers cease on the leeward side of the Cascade and Sierra Nevada Mountains, with that area receiving little or no rain. The numerous desert regions in the West are found on the leeward side of the mountains. Following a turbulent passage over the higher slopes of the Rockies, losing still more of its moisture, the air then descends the eastern slopes, being heated adiabatically, and reaches the plains of the Middle West.

(1) *Properties.*—When the air reaches the Great Plains the modifying influences of turbulence, subsidence, the cooling effect of the surface, and the loss of moisture through precipitation cause the properties of the air mass to be quite different from those found on the Pacific coast.

(*a*) *Temperature.*—The temperature at all levels is considerably higher. Temperatures are 30° F. to 35° F. in the morning and have quite a large diurnal variation.

(*b*) *Moisture content.*—The air reaching the surface is quite dry, with specific humidities of 3g/kg. or lower. Relative humidities are less than 50 percent. Values of lift are very high.

(*c*) *Lapse rate.*—The stabilizing influence of turbulence, subsidence, and adiabatic heating render the lapse rate very stable. Usually an inversion is found at low levels.

(2) *Flying conditions.*—Flying in Pp air in the Middle West in the absence of any frontal zones is very pleasant. It is marked by the absence of clouds or by any form of precipitation. Visibility will be limited only by smoke and haze near large cities.

64. Polar Atlantic (Pa).—*a. Source region.*—This air mass is an infrequent visitor to the United States and even then only to the northeast section. This is due to the fact that the prevailing air movement is from west to east. The source region is the North Atlantic Ocean adjacent to the continent and north of the warm Gulf Stream.

b. Properties.—This air is merely Pc air modified by passage over the Atlantic. The Pc air moves over the east coast as a cold outbreak, circulates over the North Atlantic, and retrogrades westward as a Pa air mass. Since the North Atlantic is from 8° to 10° C. (14° to 18° F.) colder than the North Pacific, the modification of the Pc air is much less marked.

(1) *Temperature.*—The water temperature at the source is near 0° C. (32° F.). The temperature of the air therefore is quite cold.

(2) *Moisture content.*—Moisture is absorbed during water trajectory

with only lower levels affected. The specific humidity will be around 3g/kg.

(3) *Lapse rate.*—The lower levels of the PA air are cold, moist, and moderately unstable. The upper levels will be dry and stable.

c. Flying conditions.—Flying conditions along the New England coast in Polar Atlantic air will have the following characteristics:

(1) Due to shallow unstable layer and the marked stability aloft, cloud systems will be stratiform.

(2) Precipitation is not characterized by instability showers, but by misting rains and snow.

(3) Ceilings range from 800 to 1,500 feet in strong winds, becoming near zero in precipitation. Tops of clouds are usually below 6,000

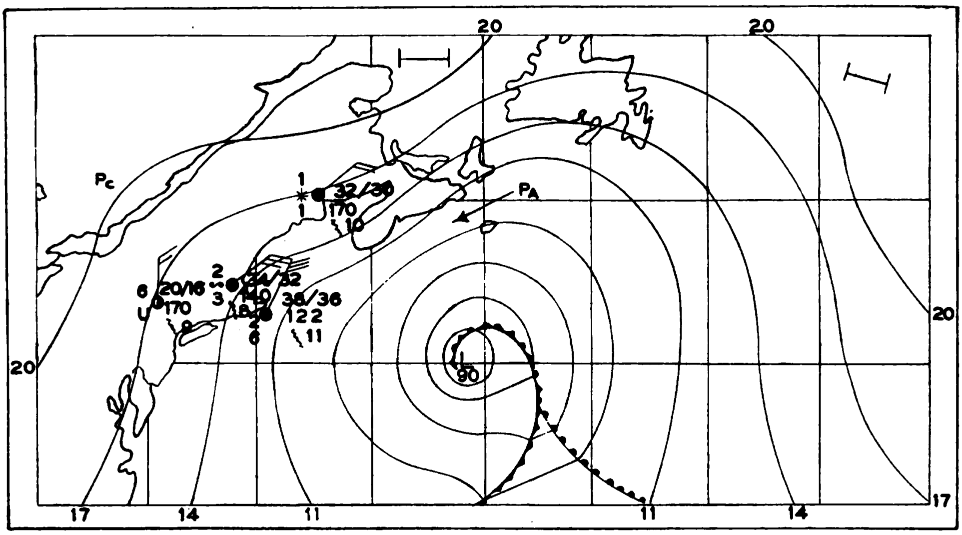


FIGURE 105.—A New England "Nor'easter" with PA air.

to 8,000 feet. Visibilities are from 3 to 5 miles decreasing to less than 1 mile in rain or snow.

(4) Since these outbreaks are usually associated with a deepening cyclone offshore, high-wind velocities are usually found. Turbulence is quite marked due to the rapid flow of air over the rough country. The unstable layer is quite shallow and the stable lapse rate aloft makes the air smooth above 8,000 feet.

(5) Severe icing takes place readily in lower levels. Clear ice will normally not be found above 8,000 feet. Outbreaks of this sort give the typical "Northeaster" of New England.

(6) A particular hazard in an influx of this type of air is the rapidity with which the flying conditions can become very hazardous. The usual set-up for a situation of this type to occur is as follows:

(*a*) New England is occupied by Pc air with clear skies, low temperature, and northwest winds.

(*b*) A deep low develops off the east coast.

(*c*) The winds shift from northwest to northeast, the temperature rises, low stratocumulus clouds appear, and the visibility and ceiling decrease rapidly. Misting rain and snow begin.

65. Tropical Gulf and Tropical Atlantic (TG and TA).—*a. Source region.*—These two air masses have as their source the uniformly warm surfaces of the Gulf of Mexico, the Caribbean Sea, and the Sargasso Sea. The properties of these two air masses are practically the same, so they shall be discussed together. The sea temperatures in winter run about 25° to 26° C. (77° to 79° F.). The air has the following properties:

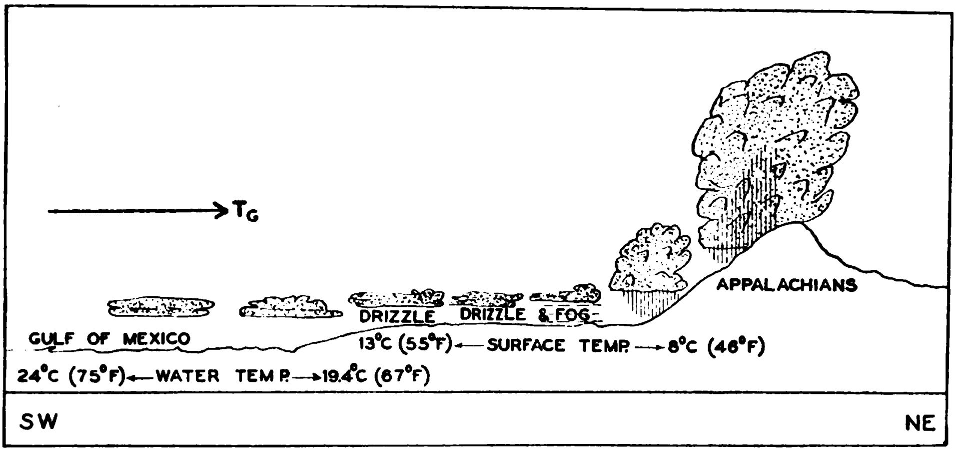


FIGURE 106.—TG air moving northward.

(1) *Temperature.*—The air is very warm, with temperatures around 75° F.

(2) *Moisture content.*—The lower levels are very moist with values of specific humidity of 12 to 15g/kg. Due to the subsidence effect of air around the Azores HIGH, the moisture content decreases rapidly with height.

(3) *Lapse rate.*—TG and TA air masses are characterized by conditional instability. However, because of the amount of lift required, this instability is rarely released except along an active front.

b. In southern United States.—The modification in this type of air as it moves northward over a cold land surface is very gradual as compared to the very rapid modification of the Polar Continental air moving southward. Modifications of the source properties are usually limited to the lower levels.

(1) *Properties.*—(*a*) *Temperature.*—The temperature of the land along the Gulf coast at night is normally from 4° to 5° C. (7° to 9° F.) colder than the waters of the Gulf of Mexico. Thus the temperature

at the surface will decrease to around 65° F. with a pronounced inversion at 2,000 feet. During the day, the sun's rays will raise the temperature from 80° to 85° F. As the air moves farther north and encounters snow-covered surfaces and colder land, the temperature will decrease even further.

(*b*) *Moisture content*.—The values of the specific humidity remain practically the same with perhaps a slight decrease. However, due to the decrease in temperature, the lift necessary to saturate the air is much less.

(*c*) *Lapse rate*.—The air remains conditionally unstable, but a marked stratification is set up in the lower levels.

(2) *Flying conditions*.—In areas removed from frontal zones the following flying conditions will be encountered:

(*a*) The skies will normally be clear except during the night and in early morning. The cooling of the warm moist air in contact with the cold surface usually forms a low stratus deck, which in the more southerly latitudes breaks and dissipates during the morning. Along the forward edge of the TG air, dense fog and mist are frequently found. The farther northward this warm moist current moves, the more persistent the low cloudiness becomes. Although the air is conditionally unstable, the very stable lower layers prevent the formation of cumulus type clouds. Before the TG air has moved very far northward, it is usually forced to ascend a cold air mass in the Middle West or eastern United States. Frequently, forced ascent by the TG air over the Appalachian mountains releases the conditional instability and cumulus type clouds are found.

(*b*) The only type air mass precipitation to be found in this air is a heavy mist or drizzle. This drizzle is seldom found along the Gulf coast except in connection with active fronts or with sufficient convergence to produce the necessary lift. This lift can be supplied by the higher terrain of west Texas or the Appalachians and showery precipitation will result.

(*c*) Ceilings will be unlimited in the absence of the stratus clouds. The low stratus will usually form at 1,500 feet, late at night, decreasing throughout the night to less than 500 feet. A slight improvement will be noticed after sunrise, but it sometimes is followed by decreasing ceilings for the next hour. Depending on the synoptic situation, the clouds become broken late in the morning with an unlimited ceiling throughout the remainder of the day. As the air moves northward, the ceilings become lower with frequent fog and mist. Improvement is much less rapid and the cloudiness tends to persist. Tops of the clouds will range from 2,000 feet along the coast to 4,000 feet in the

Central States. Visibilities are usually 5 miles at night and frequently less than 3 miles. Near large cities, the prevalence of smoke reduces visibility throughout the day to less than 6 miles.

(*d*) The stability of the air precludes any turbulence within the air mass in flat country.

(*e*) The inherent warmth of the air prevents any danger of icing except over mountainous country.

66. Polar Basin (PB).—During the winter months, old Polar Pacific air or Polar Continental air moves into the Great Basin and stagnates for long periods. The anticyclone identified with this type situation is associated with oscillations of the tropopause in this vicinity. A deep low forming in the Gulf of Alaska will cause a corresponding high over the Northwest. The characteristics of the air masses associated with this quasistationary anticyclone are quite different from those characteristics observed in rapidly moving PP air across the Rockies and therefore the air mass is usually listed separately from transitional PP or PC.

a. Source region.—The source region for this air is the Great Basin and the Columbia Plateau, an area lying between the Rockies and the Sierra Nevada and Cascade ranges. The subsidence of the stagnating air together with the cold land surface determine what the properties will be.

(1) *Temperature.*—The PB air has a very wide range of temperature at the surface becoming quite low, near freezing at night and 10° to 15° C. during the day.

(2) *Moisture content.*—The specific humidity ranges from 3 g/kg. at the surface to less than 1 g/kg. at 13,000 feet. The high temperature on the surface and aloft gives very low values for the relative humidity and thus requires a lift of from 7,000 to 8,000 feet to saturate the air.

(3) *Lapse rate.*—The warming effect of subsidence produces fairly high temperatures aloft. This, together with the cooling effect near the surface levels produces a very marked inversion, with an increase in temperature at several thousand feet from 10° to 12° C. The lapse rate is very stable.

b. In Middle West or along Pacific coast.—(1) *Properties.*—Any movement of the PB air from its source region to the east or west will cause adiabatic heating as it descends from the Rockies, the Cascades, or the Sierra Nevada mountains. This "foehn" effect causes the air to become even warmer, drier, and more stable. The properties of the air along the west coast or in the Middle West will be the same.

(2) *Flying conditions.*—(*a*) Flying conditions in this type air in its source region or in the Middle West and Pacific coast will be characterized by clear skies, unlimited ceilings, and no precipitation. However, the following situation, which is of special significance to the pilot, frequently develops along the west coast. The warm air flows out of the Great Basin under the influence of a weak pressure gradient. In the late afternoon and evening the sea breeze is strong enough to overcome the gradient in the lower levels, thus bringing a moist cool air in to the coast. Turbulence assists in setting up a distinct moisture and temperature discontinuity and radiation from this moisture discontinuity causes formation of a low stratus with a ceiling of 1,000 to 1,500 feet which rapidly decreases to less than 500 feet. Visibility often becomes less than 1 mile. The formation of this very hazardous situation can take place in a very short time and pilots flying in that vicinity during such a situation should be especially careful.

(*b*) Another local effect occurs quite frequently in the San Joaquin valley which involves PB air. An outbreak of warm, dry air from the interior traps a thin layer of cold, moist air in the San Joaquin valley. Stratus forms due to radiation with very low ceilings. Continued radiation during each night and absorption and reflection of solar radiation by the cloud layer, accentuates the low cloudiness. This situation sometimes persists for a week or more and can only be ended by a strong surface cold front.

67. Tropical Pacific (TP).—*a. Source region.*—The most important tropical maritime air mass affecting the western part of the United States in winter is the tropical Pacific air mass. This type air is associated with the semipermanent Pacific anticyclone, which is situated in winter in the southern Pacific Ocean between 25° and 35° N. latitude.

(1) *Properties.*—The air properties are affected by the relative coldness of the ocean and the anticyclonic circulation. These properties are as follows:

(*a*) *Temperature.*—The sea surface temperatures range from 14° to 19° C. (57° to 66° F.), as compared to 22° to 26° C. (71° to 79° F.) for TG or TA.

(*b*) *Moisture content.*—The quantity of moisture contained in TP air is rather low for a tropical air mass. The lift necessary to saturate layers of this air is very high except at the surface. The moisture content decreases rather rapidly with altitude.

(*c*) *Lapse rate.*—Low surface temperatures and subsidence effect tend to stabilize lapse rates. The air is not conditionally unstable.

(2) *Flying conditions.*—The weather in the source region is usually

good and free from condensation forms until the TP air has moved northward over colder water.

b. *Along Pacific coast.*—The normal path for the migratory cyclones lies in the more northerly latitudes. Frequently these disturbances move to more southerly latitudes and break down the Pacific HIGH or force it southward. In this case, the pressure gradient causes an onshore flow of tropical air and the Tropical Pacific air then occupies the west coast.

Tropical Pacific air seldom reaches the surface east of the Sierra Nevadas. However, TP air frequently moves eastward aloft over polar air masses bringing general blizzard conditions.

(1) *Properties.*—The movement northward over colder waters to the coast and consequent movement over land result in a gradual modification of the source properties.

(*a*) *Temperature.*—Contact with colder water lowers temperature gradually.

(*b*) *Moisture content.*—The values of "q" decrease slightly but the relative humidity increases at all levels.

(*c*) *Lapse rate.*—The air remains quite stable.

(2) *Flying conditions.*—The appearance of this air at the surface along the west coast is marked by those phenomena observed in stable air masses.

(*a*) Cloud systems will be stratus or stratocumulus.

(*b*) No precipitation will be found except along mountain ranges. Even this precipitation will be of a drizzle form and not extensive.

(*c*) Ceilings will range from 500 feet to 1,500 feet with the top of the stratocumulus deck extending to 10,000 or 15,000 feet. Visibilities are good, except in precipitation.

(*d*) Since TP air is quite stable, the air will be free from turbulence.

(*e*) Icing is very infrequent.

68. Superior (S).—The Superior or Ts air, as it is sometimes known, is a warm, dry air mass frequently found at high levels, in the South and less frequently at higher levels in the North. This air is believed to originate in the upper portion of the subtropical anticyclones. It is probably poleward moving air which is slowly sinking along the middle latitudes. Thus, this air will usually be present aloft when the winds are westerly to southwesterly. Normally, Superior air at intermediate levels will indicate clear weather.

–230
70

h
9
0
1
2
3
4
5
d
h
e
h
.
y
s

d
y
e

ll

e

y

e
t
s
y
s

t
o

e
s

g
n

li
m
o
o
tl

N
p

tl
m

g

re

al
st

E

tl
ti

k
tl
is
c
in
al
S

SECTION VIII

NORTH AMERICAN SUMMER AIR MASSES

69. General.—In summer the Northern Hemisphere is inclined toward the sun. For this reason the rays of the sun strike the earth more directly, allowing more solar radiation to be absorbed by the atmosphere and by the earth. The land surfaces become heated with a rapid increase in all surface temperatures of from 15° to 20° C. (27° to 36° F.). The water temperatures change much less, usually from 6° to 8° C. The greatest increase in land and water temperatures occurs in the more northerly latitudes.

a. During this season the water surfaces are colder than the land surfaces. For this reason all polar maritime air masses usually exhibit a stable lapse rate over water but become rapidly unstable over land.

b. All summer air masses are characterized by warmth.

c. Due to the inherent warmth up to 5 or 6 kilometers, no icing will be experienced in the middle latitudes.

d. In all air masses moving over flat country, turbulence will be experienced in the middle latitudes.

e. Cloud forms in summer air masses along coastal areas are usually stratiform at night and cumuliform during the day.

70. Polar Continental (Pc).—*a. Source region.*—In summer the surface of Canada is no longer snow and ice covered. The movement of the sun northward, with resultant increase of solar radiation, heats the surface. The source properties in summer will be radically different from those found in Pc air in winter. The weather is usually clear with no precipitation.

(1) *Temperature.*—The air is relatively cool in the morning but undergoes large diurnal variations, usually ranging from 15° C. to 25° C. (27° to 45° F.).

(2) *Moisture content.*—The increased capacity of the air for moisture results in specific humidities of from 5 to 6 g/kg. Relative humidities are rather low with very large lifts necessary for saturation.

(3) *Lapse rate.*—Very steep lapse rates exist during the afternoon.

b. Modification southward.—The general circulation decreases in intensity during the summer months and outbreaks are fewer and less active. Thus a Pc air mass moving slowly southward will undergo rapid modifications in its properties.

(1) *Properties.*—(*a*) *Temperature.*—Convective heating and subsidence combine to increase the temperature at all levels.

(*b*) *Moisture content.*—The specific humidities increase rapidly. Relative humidities remain low.

(*c*) *Lapse rate.*—The air is convectively unstable in the lower levels.

(2) *Flying conditions.*—Conditions in Pc air in the Middle West will usually be as follows:

(*a*) Skies are clear, except for scattered cumulus. Cloudiness increases as the air mass moves southward.

(*b*) Precipitation is lacking.

(*c*) Ceilings and visibilities are unlimited.

(*d*) During the day the air will be quite turbulent in the lower levels but smooth above 10,000 feet.

c. Modification across Great Lakes.—Pc air reaching the States south of the Great Lakes possesses characteristics different from Pc air over the plains of the Middle West. This is probably caused by a trajectory southward across the cold Hudson Bay and the Great Lakes.

(1) *Properties.*—The variation in the modification of the properties is quite marked, especially in the lower levels.

(*a*) *Temperature.*—The temperature is from 3° to 4° C. (5° to 7° F.) colder than that found farther west.

(*b*) *Moisture content.*—Due to its water trajectory, the air contains from 1 to 3 g/kg. more moisture. The relative humidity is therefore higher with lower values of lift required.

(*c*) *Lapse rate.*—The air is conditionally unstable in the lower levels.

(2) *Flying conditions.*—Flying conditions in this air can be summarized as follows:

(*a*) Clouds are cumuliform, with early morning ground fogs found at lake shore stations.

(*b*) Scattered thundershowers occur in the early afternoon in Pc air that has moved far southward.

(*c*) Ceilings are unlimited except in fog and in precipitation. Visibilities are restricted only in the above cases.

(*d*) Mild turbulence will be experienced only in clouds. Polar Continental air in summer seldom moves into the lower latitudes as a rapidly moving outbreak. Instead the Canadian HIGH will move

slowly southward, remaining in the vicinity of the Great Lakes for days at a time. The entire area experiences the good weather associated with that type air.

71. Polar Pacific (Pp).—*a. Source region.*—During the spring, the Pacific anticyclone moves northward with the center occupying a position between the 40th and 45th parallels of latitude and between the 135th and 145th meridians. The relative coldness of the Pacific Ocean causes the high-pressure area to be more intense. This, together with the thermal low found in the southwestern United States, causes a strong pressure gradient to be directed inland. Thus a steady flow of Pp air at all levels is found throughout the summer along the west coast. Since the Pp air is now associated with the quasistationary high, the effects of subsidence are marked.

b. Modification on reaching West Coast.—Polar Pacific air moves around the Pacific anticyclone into the cold waters of the North Pacific and then southward to the west coast.

(1) *Properties.*—As it moves southward, it is heated from below. Upon reaching the Washington coast, the air mass moves over a cold current of water. This cold belt is caused by the upwelling of the colder water below the surface. Thus Pp air along the California coast is a warm air mass with stable characteristics.

(*a*) *Temperature.*—Despite the warming effect of the southward movement, the air reaches Seattle with fairly low temperatures, averaging 15° to 17° C. (59° to 63° F.). The air reaching the Central California coast is colder, averaging from 13° to 15° C. (55° to 59° F.).

(*b*) *Moisture content.*—The long water trajectory supplies the lower levels with quite a bit of moisture, giving specific humidities of 7 to 8 g/kg. The relative humidity is from 60 to 70 percent at the surface, increasing to near saturation at 2,500 feet. The moisture decreases rapidly with height above the 2,500-foot level.

(*c*) *Lapse rate.*—The high wind velocities cause turbulent mixing so that the lapse rate is quite steep in the lower levels with a slight inversion aloft. The upper levels show a rapid decrease in temperature. The cooling effect of the California waters tends to stabilize the lower layers.

(2) *Flying conditions.*—A pilot flying along the Pacific coast in summer will likely encounter the following conditions:

(*a*) Low stratus or stratocumulus clouds would be found all along the coast. These clouds are limited to the coast line except at night and during the morning when their extent inland is limited by the coast ranges. Fog is frequently found along the California coast but is usually lifted by the high wind velocities to low stratus. The low

stratus becomes fog over higher ground inland. The effect of radiation from the moisture discontinuity at 3,000 feet together with the cooling of the surface air account for this characteristic phenomena.

(*b*) Precipitation is lacking except for mist.

(*c*) Ceilings range from about 2,000 feet at Seattle to less than 800 feet at San Francisco, increasing along the southern California coast to around 1,000 to 1,500 feet. The tops of these clouds average 3,000 feet. Visibilities range from 10 miles to less than 1 mile along California coast.

(*d*) Due to its stability, the air will be very smooth. Flying conditions east of the coastal ranges will be excellent with clear skies, unlimited ceilings and visibilities prevailing. Turbulence will be noticeable in desert areas due to convective activity.

c. East of the Rockies.—At irregular intervals during the summer, the Pacific anticyclone moves onshore and Polar Pacific air crosses the mountain ranges in the West and descends into the Middle West. The trajectory of the air has carrried it into Canada and across the Rockies. Thus when it reaches the plains States it has become indistinguishable from Polar Continental air. For this reason, the label Pp or Pc can be used indiscriminately for polar air east of the Rockies.

72. Polar Atlantic (Pa).—*a. Source region.*—In the late spring and early summer the Polar Atlantic air masses play a very important role in the weather along the east coast. The North Atlantic remains very cold, with temperatures only a few degrees above freezing. This is due to the lag in the heating of large bodies of water and to the influence of drifting ice in the Labrador current. For this reason, the North Atlantic is much colder than the nearby continental areas. Pa air is actually Pc air which has moved out over the Atlantic and stagnated. Therefore in summer the air is a warm air mass or is warmer than the water surface.

(1) *Properties.*—During the warmer seasons, an anticyclone builds up over the North Atlantic, with an easterly flow toward the east coast. This high-pressure area remains nearly stationary for long periods at a time to allow marked changes to occur within the Pc air.

(2) *Flying conditions.*—Flying conditions over the water are very good except for low stratus. Ceilings are from 1,000 to 2,000 feet with excellent horizontal visibility.

b. Along east coast.—The anticyclonic circulation brings Pa air to the New England coast for as long as 1 or 2 weeks at a time. Occasionally the HIGH will move southward and the Pa air will reach the southern coastal States. As the Pa air moves southward to the

southern States, it becomes unstable and is characterized by cumulus clouds, showers, and moderate to severe turbulence.

(1) *Properties.*—Normally the movement of the air mass southward is connected with strong winds.

(*a*) *Temperature.*—Although the air is moving over warmer waters, it retains its coldness. The surface temperatures range from 5° C. (42° F.) in spring to 12° to 15° C. (53° to 59° F.) in summer.

(*b*) *Moisture content.*—The relatively low temperature prevents any big increase of moisture. The specific humidity remains fairly constant for the first 2,000 or 3,000 feet, decreasing very rapidly aloft. The relative humidity increases from moderate values to saturation at from 2,000 to 3,000 feet.

(*c*) *Lapse rate.*—The strong wind velocities mix the air in the lower levels thoroughly, setting up an adiabatic lapse rate. Above this layer, the effects of subsidence together with the turbulence cause a temperature inversion of as much as 5° C. (10° F.).

(2) *Flying conditions.*—Except in the areas of frontal activity, flying in this air in summer should not be hazardous.

(*a*) Cloud forms are stratus and stratocumulus.

(*b*) Precipitation is lacking within the air mass, except in regions of decided convergence where misting rain develops.

(*c*) Ceilings will range from 500 to 1,500 feet. Visibilities are good except very low in misting rain.

(*d*) The air is very smooth above the clouds.

73. Tropical Continental (Tc).—*a. Source region.*—The continent of North America becomes more narrow in the lower latitudes. The water area occupies much more of the earth's surface below 30° than in the middle or northerly latitudes. For this reason, almost all tropical air masses are maritime air masses. However, during the summer, air stagnating in the southwestern United States and Mexico assumes rather definite characteristics. This air is known as Tropical Continental. It is usually associated with the thermal cyclone that is semipermanent in summer in the Southwest, and its source region is Arizona, New Mexico, western Texas, and northern Mexico.

(1) *Properties.*—The properties of this air are quite different from tropical maritime air and have the following characteristics:

(*a*) *Temperature.*—The air is characterized by large diurnal variations in temperature from 30° to 40° F.

(*b*) *Moisture content.*—The air is very dry, with relative humidities of 10 to 20 percent. Very large lifts are required to saturate the air.

(*c*) *Lapse rate.*—Very steep lapse rates, often superadiabatic, are set up in the afternoon.

(2) *Flying conditions.*—Excellent flying weather is found throughout the Southwest during the summer. The sky is clear, with unlimited ceilings and visibilities of from 50 to 75 miles. All forms of precipitation are absent. The air will be smooth at night, but turbulent over the desert regions in the afternoon, often to above 10,000 feet.

b. In Middle West.—Normally the flow of air is northward and northeastward over the Rocky Mountain region. However, infrequently during the summer, Tc air will move eastward into the Middle West. At these times the Middle West will suffer from extremely hot days and a period of drought. This air mass quickly loses its identity and is seldom found east of the Mississippi River.

74. Tropical Pacific (TP).—*a. Source region.*—It has been noted in the discussion of PP air masses in summer, that the Pacific anticyclone moves to the northward, and that a strong westerly or northwesterly flow exists throughout the summer. With this prevailing flow of PP air, TP air is seldom found along the coastal regions, especially at the surface. The source region of TP air in summer is the southern and southwestern part of the Pacific anticyclone.

(1) *Properties.*—The air is somewhat warmer and more moist, but possesses practically the same characteristics as in winter.

(2) *Flying conditions.*—The Tropical Pacific air moves northward around the eastern edge of the HIGH, and passes over colder waters. This cooling effect gives use to fog and mist over most of the Pacific north of latitude 45°.

b. Aloft in western States.—The presence of a thermal low in Arizona and Utah frequently brings tropical Pacific air northward. This air is characterized by warmth and moisture with values of specific humidity averaging 10 to 12 g/kg. The presence of the northward moving moist tongue of air over the mountains is shown by frequent thunderstorms and wide areas of precipitation.

75. Tropical Gulf and Tropical Atlantic (TG and TA).—*a. Source region.*—In summer, the most important air masses affecting central, southern, and eastern United States are tropical Gulf and tropical Atlantic. The polar front has receded northward and occupies a position near the Great Lakes region. The combination of the formation of a low-pressure area over the continental area and the development of the Bermuda anticyclone results in a continuous flow of TG or TA air into the central and eastern United States. This accounts for the heat and oppressive humidity characteristic of these regions. The source region properties in summer are very similar to those in winter. The surface temperature over the Gulf and

Caribbean in summer are from 2° to 4° C. warmer than in winter, but the difference increases toward the coast. The air is, therefore, warmer, has a greater capacity for moisture, and exhibits a higher degree of potential instability. The large amounts of moisture present indicate a large store of available energy which accounts for the activity found in the southern States during the summer.

b. Over the continent.—The anticyclonic circulation brings the warm TG air over a surface which is still warmer and therefore this air exhibits the characteristics of a cold air mass.

(1) *Properties.*—(*a*) *Temperature.*—As the TG air moves over the land, the temperature increases to 85° to 95° F.

(*b*) *Moisture content.*—The values of "q" are around 20 g/kg. The high moisture content of the air results in high values of relative humidity and low values of lift required for saturation. Moisture is lost through precipitation as the air mass moves northward.

(*c*) *Lapse rate.*—The increase of temperature at the surface tends to increase the degree of instability. Frequently, during the afternoon, superadiabatic lapse rates are established.

(2) *Flying characteristics.*—The degree of potential instability is so marked in TG air that any occurrence that will provide sufficient lift will release the large amount of potential energy available. The necessary lift to bring the air to saturation can be provided by insolational heating, by converging winds aloft or on the surface, or by an isallobaric low. In many cases, intense activity can occur with any of the above effects. Normally, summer flying weather will be contact, except for some of the conditions listed below.

(*a*) Low stratus and stratocumulus form in the early morning within 250 to 300 miles of the Gulf coast. This is caused in some cases by the advent of a moist, cool layer of air brought in by the sea breeze late in the afternoon. The presence of this more moist air at the surface, together with the effect of turbulence, results in a temperature inversion and moisture discontinuity at 1,500 to 2,000 feet. Farther than 150 miles from the coast, the inversion is usually caused by turbulence, with the additional moisture being supplied by local sources. Radiation from the top of this layer lowers the temperature sufficiently to form a low stratus overcast. This stratus usually forms near midnight or later. Insolational heating during the morning causes the stratus deck to break and a continued rise in temperature results in the formation of cumulus clouds. If the TG air is at least 7,000 feet thick or thicker and possesses a steep enough lapse rate of the order of 6° to 8° C. decrease per kilometer, especially in the upper layers, showers and thunderstorms may develop, especially along the weak

fronts that frequently exist. These showers and thunderstorms are usually so widely scattered that they afford no hazard to the observant pilot. Thunderstorms are found more frequently and are less scattered east of the Mississippi. With southeast winds on the surface and aloft in west Texas, sufficient lift is afforded by the higher terrain to give cumulus which frequently develop into rather intense thunderstorms. These also are scattered, but are of a more general nature than those found in east Texas and Louisiana. The same situation develops with TG air moving over the Appalachian mountains. Movement of TA air northward along the Atlantic coast is over a cool ocean current. This frequently results in a deep fog off the coast, which

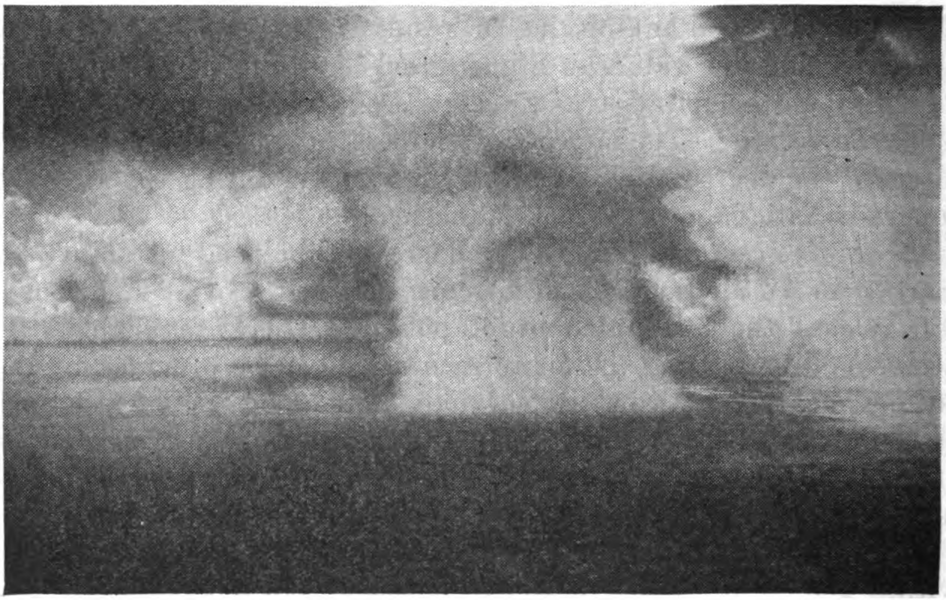


FIGURE 108.—Afternoon shower in TG.

moves inland under the influence of the sea breeze. Strong winds sometimes lift the fog to a low stratus.

(*b*) Precipitation is in the form of showers. The synoptic situation and structure of the air indicates the intensity of the precipitation. Frequent hailstorms are associated with these thunderstorms.

(*c*) Ceilings in the stratus clouds will usually be 1,500 to 2,000 feet in early morning hours, descreasing to 500 to 1,000 feet later in the morning. Ceilings in the cumulus clouds will range from 3,000 to 4,000 feet decreasing in showers to less than 1,000 feet becoming 200 to 400 feet in thunderstorms. Visibilities remain good except in fog, showers, or thunderstorms where they may become less than 1 or 2 miles. Ceilings and visibilities in the Atlantic coast fog are usually

TM

very low except where high-wind velocities raise them to 500 to 800 feet.

(*d*) The air above a few thousand feet is quite smooth, outside of the clouds. However, turbulence can be very severe in thunderstorms. Thunderstorms offer extremely hazardous flying conditions and should be avoided.

(*e*) Severe icing conditions exist above 16,000 to 18,000 feet.

SECTION IX

NORTH AMERICAN MOIST FRONTS

76. General.—*a*. Moist fronts may be defined as those fronts in which one of the adjacent air masses is a maritime mass of air fresh from the source region. The following is a list of the moist fronts found in the United States:

Pc–Tg	Pc–Ta
Pp–Tg	Pp–Ta
Pa–Tg	Pa–Ta
Pp–Tp	Tc–Tg

b. Tg and Ta have practically the same characteristics; therefore, it is possible to combine the discussions of the Pc–Tg and Pc–Ta fronts. Similarly, only one of each pair of Pp–Tg, Pp–Ta, Pa–Tg, and Pa–Ta need be discussed. Only those points of interest to the pilot will be covered. Each front will be discussed for winter and summer when its importance justifies it.

77. Polar Continental—Tropical Gulf (Pc–Tg) **in winter.**—During the winter season, the Pc–Tg fronts are the most active of all fronts, since the properties of these air masses show the greatest contrast. Very often a Pc air mass moves rapidly southward as a "cold outbreak" into the central and southern part of the United States and displaces Tg air. The front is then acting as a cold front. After the Pc air has moved into the United States and stagnated, the anticyclonic circulation over the Gulf of Mexico causes a wave in the polar front which starts moving northward. The discontinuity sur-

face now acts as a warm front, with the warm tropical air overrunning the polar air.

a. The region of frontogenesis occupies the Southern and Southeastern States, oscillating back and forth across the South Central States throughout the winter.

b. The Pc–Tg front stretches in a northeast-southwest direction, with waves along the front usually moving to the northeast.

c. The Pc–Tg cold front is usually the sharpest and most distinct of all fronts, with a decided wind shift from southwest to northwest and a pronounced trough and a rapid rise in pressure following the passage of the front. Since the temperature of the Tg air averages 55° to 70° F. and that of the Pc air is usually less than 32° F., a very decided drop in temperature will ensue. In addition, the dew point will fall very rapidly.

d. The Pc cold front moves with 80 to 100 percent of the velocity of that component of the gradient wind perpendicular to the front. The velocity averages 35 to 40 miles per hour in the more northerly part of the United States decreasing to 25 to 30 miles per hour in the South and Southwest.

e. A pilot flying in a Tg air mass toward the approaching cold front may expect to run into weather of the type listed below:

(1) The airplane will first encounter altocumulus clouds about 50 miles from the front, which will thicken and lower rapidly to cumulus and cumulonimbus. As in Pc air masses, a stratocumulus layer develops after the front passes due to turbulence and instability in lower layers.

(2) Heavy instability showers with mild to severe thunderstorms will occur. The rapidly moving cold air aloft will often overrun the Tg air, setting up violent convections from above resulting in severe thunderstorms as far as 100 to 150 miles ahead of the front. Frequently, the rapid fall in pressure as a well-defined trough approaches is sufficient to set off the instability in the Tg air. Following passage of the front, the showers cease and conditions improve rapidly.

(3) Ceilings will decrease from 5,000 or 6,000 feet ahead of the front to zero in showers at the front. Immediately following the passage of the front, ceilings will increase 1,500 to 2,000 feet. Visibilities remain good except becoming zero in showers and storms.

(4) Turbulence is very severe in the immediate frontal zone and in prefrontal thunderstorms.

(5) Clear ice can become quite severe in frontal zones and in associated showers. By flying fairly low or by evading thunderstorms, icing can be avoided.

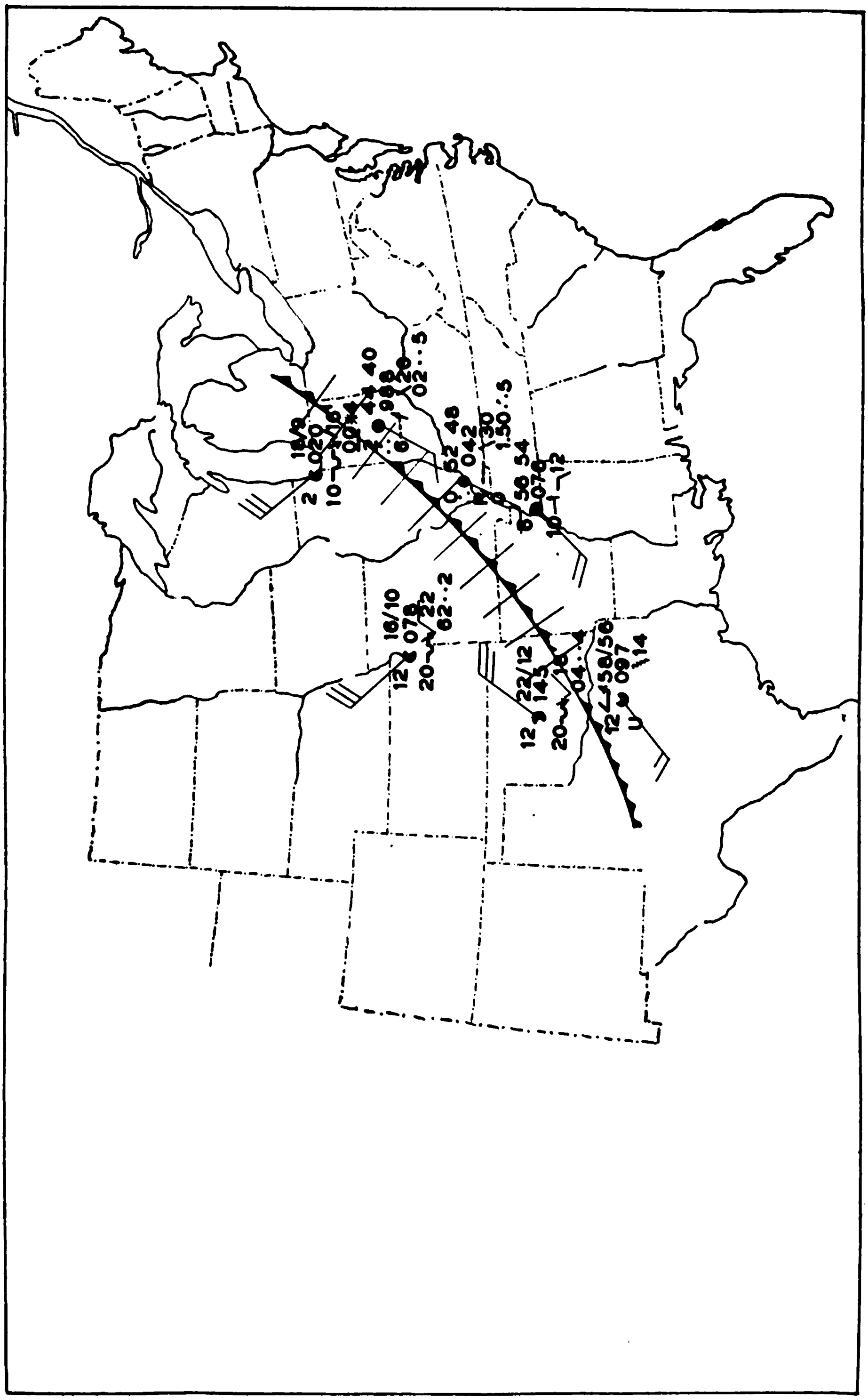


FIGURE 110.—Pc–Tg front in winter.

f. Very frequently during the winter, the Pc air following the cold front will reach the southernmost States as a shallow wedge. The movement of the wedge underneath the warm air will cause the TG air to flow up the shallow slope of the cold front. This is known as a "passive up glide front," since the warm air is moving more slowly than the shallow cold air and thus is moving up the cold front only relatively. In this case, the usual clearing following passage of a cold front is not found. A stratified cloud system results from the gradual lifting of the tropical air up the flat slope of the cold front.

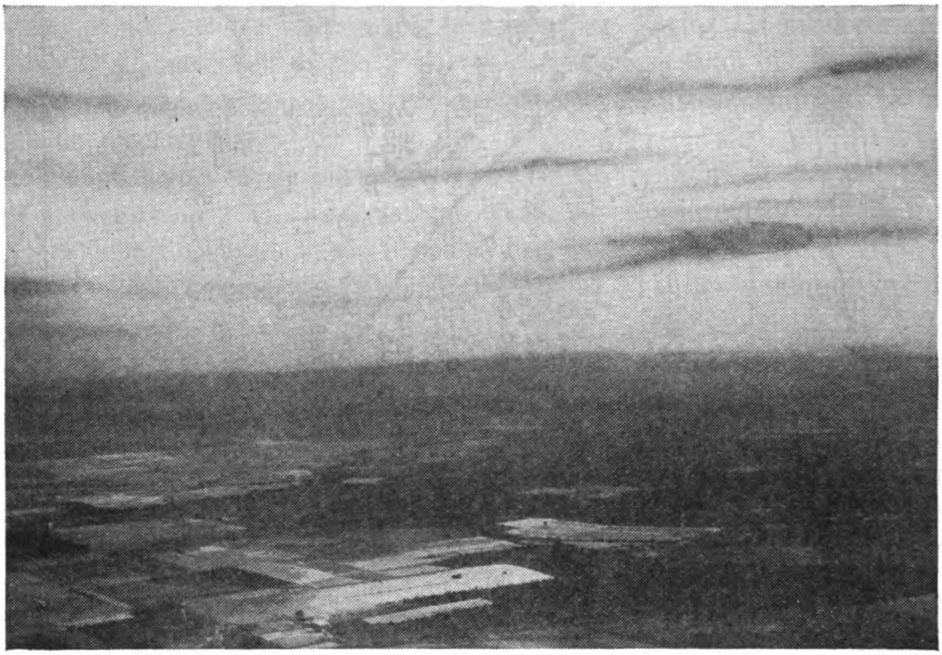


FIGURE 111.—Stratocumulus clouds ahead of wave on stationary TG–Pc front, lying along Texas coast. Photograph taken looking toward center of wave situated south of Houston, at Devine, Tex., March 1, 1939.

If the cold air continues to move southward and no wave in the front forms, the cloud system soon breaks and dissipates leaving only the cold air mass type lower clouds. However, the cold air mass often decelerates and a wave forms in the Gulf with a formation of a warm front and resultant active overrunning.

g. In many instances the Pc cold front will decelerate upon reaching the Gulf and become a stationary front. Along this front frontogenesis takes place with a northward movement of the Tropical Gulf air. This wave formation may take place in the Gulf and move on shore or it may develop on shore. The deceleration of the cold front and the usual resultant formation of the wave may be expected to occur when the primary low pressure center associated with the out-

break lies above 40° latitude. The more intense the Low the farther north it can be without the deceleration.

h. The warm, moist air overrunning the cold polar air presents, in most cases, an idealized warm front structure. Flying conditions in or near this frontal zone will be as follows:

(1) The sequence of clouds will follow closely those of the ideal system. First, cirrus, then cirrostratus, and altostratus in the upper system. Within 75 miles of the front, the clouds thicken and lower to nimbostratus, stratocumulus, and stratus. The clouds are in layers and flights over the lower system and between layers can be made quite easily.

(2) Precipitation is usually steady but light to moderate in intensity. Precipitation starts falling out of the altostratus, usually evaporating, but forming lower clouds near the front. The precipitation continues for extended periods with large amounts recorded. Thunderstorms occur infrequently and usually are high, level storms.

(3) Ceilings are unlimited in the higher clouds, decreasing slowly to 1,000 to 2,000 feet and 800 feet to zero just ahead of the front. Rain falling through the Pc air frequently results in the formation of clouds with very low ceilings. Lower clouds can form very rapidly in Pc air at night at a good distance from the front. The convergence due to the approaching front together with the high relative humidities of the Pc air is sufficient to form very low clouds in a very short time. Fog and mist are a frequent occurrence ahead of a TG warm front, sometimes extending 100 to 200 miles ahead of the front. This condition is found when Pc air becomes quite shallow throughout central United States. Visibilities in the Pc air ahead of the front are usually from 4 to 6 miles, decreasing very rapidly in precipitation as the front approaches. The prevalence of fog and mist ahead of the front results in visibilities less than 1 mile. Watch carefully the temperature-dew point difference and beware of light winds.

(4) The stability of the Pc air prevents any turbulence below the warm front. If the slope of the front is steep enough to release the conditional instability, turbulence may result. However, since it is a large-scale movement of the air mass upward, the turbulence will be only light to moderate.

(5) In the vicinity of the front, where rain from the overrunning air is forming lower clouds in the polar air, icing conditions may be moderate to severe. In regions removed from the front, clear ice will usually not be found. Above the warm front, if the instability is being released, clear ice may become quite a hazard at high levels. Usually, flights may be made between layers with little fear of icing.

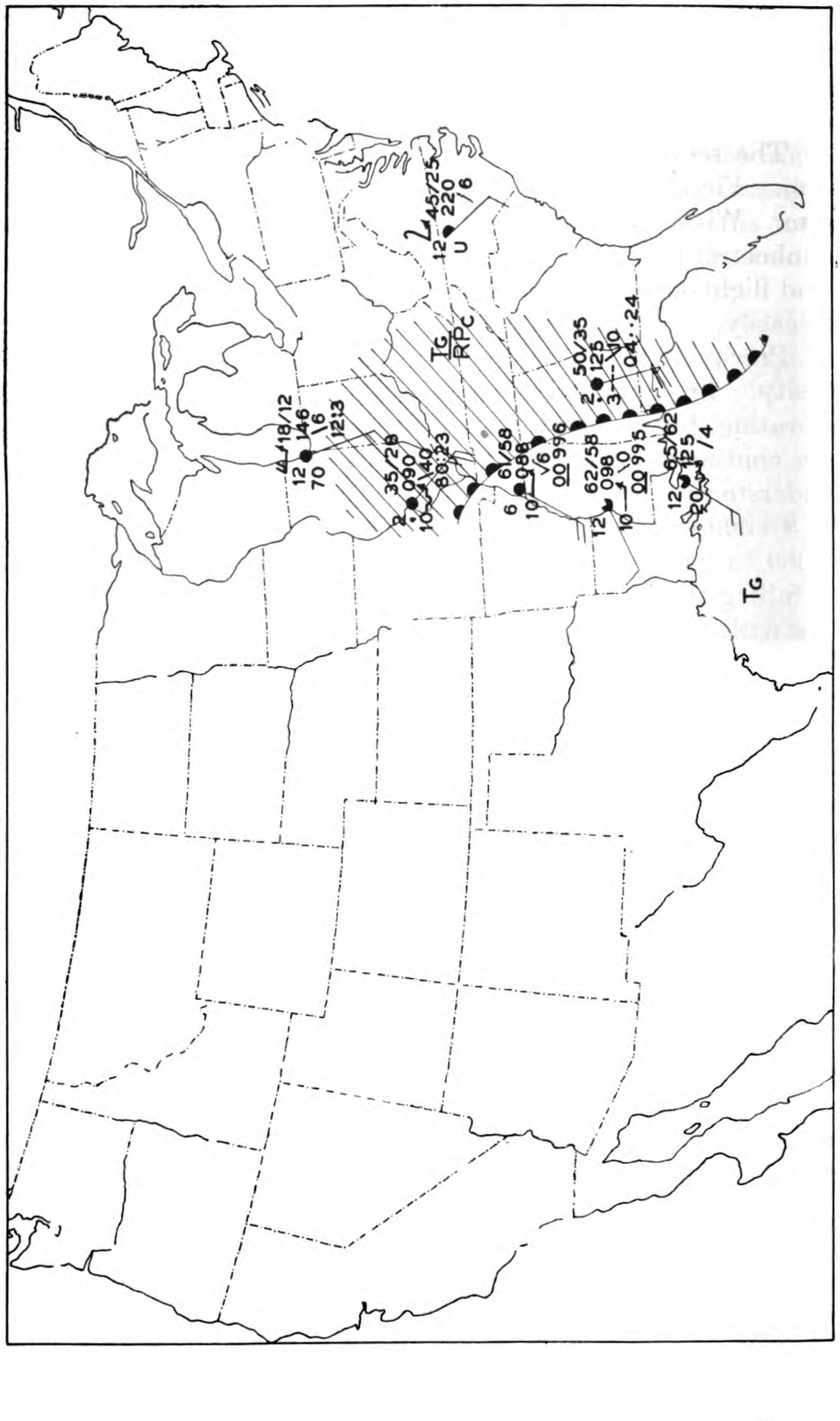


FIGURE 112.—TG-PC warm front in winter.

i. A Pc outbreak in winter is preceded by a gradual building up of high pressure and the appearance of low temperatures in northwest Canada. There is often an extended delay, with the Pc front oscillating in Canada, finally breaking out very rapidly. The movement southward usually follows the eastward movement of a migratory cyclone from the Pacific to the Middle West. Finally, the formation of waves on a Pc–Tg front results in intense cyclones which accelerate southward movement of Pc air.

j. Oftentimes during the winter, with the development of an intense cyclone north or east of the Great Lakes, the appearance of a fairly well-defined front is noted in the westerly quadrant of the Low. This is due to the modification of Pc air moving over the Great Lakes more rapidly than the air preceding it. The front is marked by a well-defined wind shift line from west to north and by the snow flurries in the frontal zone. The front seldom extends above 6,000 feet with the more rapidly moving colder air underrunning the modified surface air. This explains the occurrence of the continual snow flurries along the front.

78. Polar Continental—Tropical Gulf (Pc–Tg) **in summer.**—The similarity between Pc and Pp in summer has been noted. Therefore Pc–Tg and Pp–Tg fronts in summer may be discussed together.

a. In summer, the polar front moves northward to the Great Lakes region and oscillates very leisurely across the middle of the country. Since the Pc or Pp air is rapidly heated in its movement southward, very little difference exists in the temperatures across the fronts. The fronts become very indistinct. The air masses move very slowly and are associated with flat pressure systems. The fronts move into the southern States infrequently.

b. In the Pc–Tg cold front—

(1) The clouds are usually cumuliform.

(2) The precipitation is in the form of showers or moderate to heavy rain from thunderstorms, ahead and along the front.

(3) Due to the low relative humidities, ceilings are usually greater than 2,000 feet except becoming less than 800 feet in severe thunderstorms. Ceilings do not drop as low as they do in winter except in extreme cases. Even then, the ceilings remain very low only during the period of heaviest precipitation. This period usually lasts for less than 1 hour. Since the thunderstorms are always scattered, the bad weather never covers a large area at one time. Therefore, conditions usually are contact, if thunderstorms are carefully avoided. Visibilities remain good but decrease rapidly in the heavy precipitation.

(4) Turbulence is very severe in thunderstorms. However, the

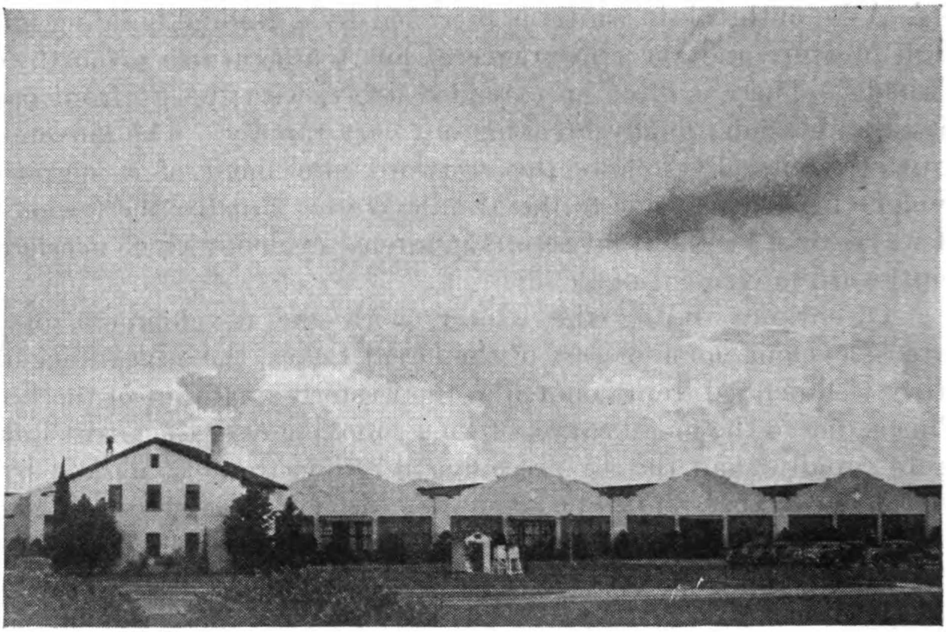


FIGURE 113.—High level thunderstorm occurring in vicinity of station. Altostratus, fractocumulus, and fractostratus are shown. Photograph taken looking away (west) from a Pc-Tg cold front approaching Randolph Field, Tex., September 16, 1939.

FIGURE 114.—Looking toward (NW.) the front mentioned in figure 113. Frontal clouds are stratus and stratocumulus, with altostratus above. Photograph taken at 10:50 a. m., with the front passing at 11:20 a. m.

storms are scattered and by avoiding the cumulus clouds near the storm a careful pilot should have no difficulty.

(5) Icing is infrequent except at very high altitudes.

79. Polar Pacific—Tropical Gulf (Pp–Tg) **in winter.**—Frequently during the winter the migratory cyclones moving eastward from the Pacific follow a more southerly path. Reaching the eastern slopes of the Rockies the cyclones intensify. This results in a strong northward flow of Tg air and a southeasterly flow of Pp air modified by the surface and the mountains. The front remains fairly inactive until it reaches central Texas where activity usually begins.

a. The area of frontogenesis lies along the eastern slope of the Rockies, extending eastward to the Mississippi.

b. The axis of the Pp–Tg front runs northeast and southwest with the associated Low centered in the Middle West. The cyclone moves to the northeast in compliance with the flow of tropical air.

c. The front normally moves eastward as a cold front. However, it frequently goes aloft, especially during the spring and fall, as an upper cold front.

d. In the Pp–Tg cold front, the Pp air has been warmed and dried out by its movement over the mountains. Thus, we would expect less activity because of the interactions between this air and the tropical air than we found in the Pc–Tg air masses. The Pp cold front moving southeastward usually encounters a modified form of polar air in west Texas, and east of the Fort Worth-Oklahoma City line meets the northward moving Tg air. Thus, the major part of the activity will lie east of that line. The frontal weather along the Panhandle is marked by partial cloudiness with no precipitation. When the "dust bowl," or the area in southeast Colorado, western Kansas, and the Oklahoma and Texas Panhandles, has experienced an extended period of little or no rain, a dust storm will move southward with the Pp air. The condition of the ground can be estimated from past precipitation and a snow cover chart. If a period of several weeks of dry weather has occurred, the surface soil will become loose. The strong wind velocities associated with the deepening cyclone will carry the dust aloft to very high levels, and it will sometimes reach the east coast. These dust storms usually occur in spring.

(1) The approach of the Pp cold front is usually preceded by the appearance of high clouds from the southwest. The frontal clouds east of Texas are cumuliform. As the front moves eastward, the cloudiness ahead of the front increases and lowers.

(2) The precipitation is in the form of showers and moderate to heavy rain from thunderstorms. The precipitation increases eastward

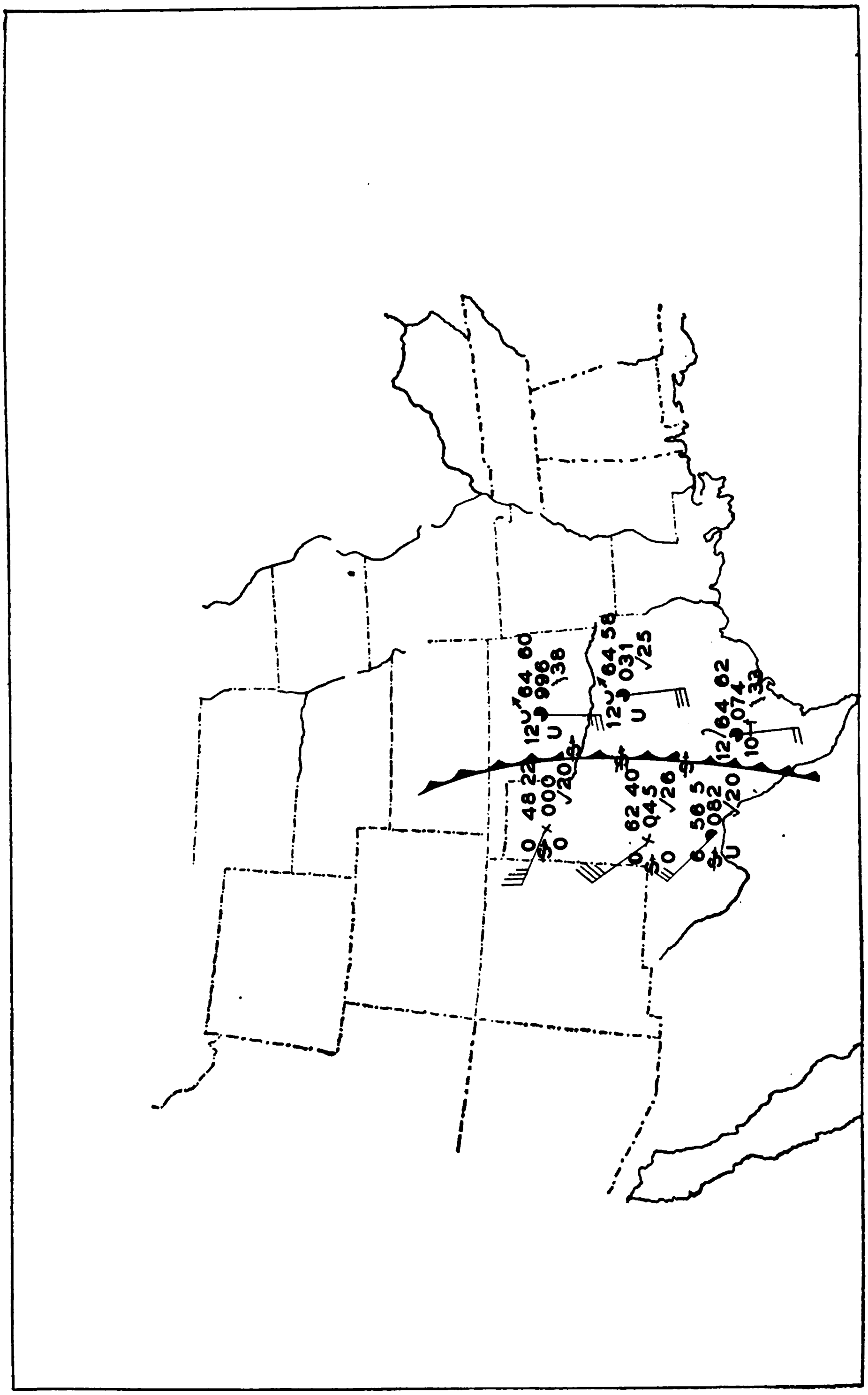


FIGURE 115.—PP-TG cold front in winter.

in intensity and amount. In the early spring, very severe thunderstorms accompany and precede the front.

(3) Ceilings west of the Oklahoma City-Fort Worth-Corpus Christi line are unlimited in scattered clouds. East of the line, as cloudiness increases, the ceilings lower to 2,000 to 4,000 feet, becoming less than 1,000 feet in precipitation. Visibilities remain good, lowering in precipitation. Ceilings and visibilities in the dust become zero very rapidly, sometimes remaining low for several days in Texas, but improving rapidly in the east. Any precipitation minimizes the dust.

(4) In the Southwest, the strong wind velocities together with the rough surface cause moderate turbulence throughout the area. Moderate to light turbulence is found east of Texas, except in thunderstorms, where severe turbulence will be found.

(5) Moderate clear ice is found above 10,000 feet along or ahead of the front.

(6) The front moves with the gradient wind which is usually around 25 to 30 miles per hour. The velocity of the front decreases east of Texas to 15 to 20 miles per hour.

(7) The development of the Low usually brings about a flow of Pc air southward. The Pc front sometimes overtakes the Pp front east of the Mississippi.

e. (1) At times during winter and frequently during spring, the Pp air moves across the Southwest and South as a Pp–Tg upper cold front. The very severe thunderstorms which occur during the spring in this area are caused in most cases by these upper fronts. The surface front usually remains stationary in west Texas, while the Pp air marches across the more dense Tg air as an upper cold front. The density curves at El Paso and San Antonio will resemble that drawn in figure 116. Other means of distinguishing this type front are as follows:

(*a*) Wind shift aloft from southerly to westerly.

(*b*) Pressure change discontinuity 100 to 200 miles ahead of surface front.

(*c*) Considerable cloudiness and precipitation well ahead of the surface front, diminishing in intensity westward.

(2) Mixing usually destroys the upper front in the eastern part of the United States. However, upper fronts do occur quite often on the east coast.

f. Tg–Ppo warm front, after the polar cold front has moved well to the east, the polar air mass occupies the country east of the Rockies. As the polar anticyclone moves slowly eastward, the anticyclonic

circulation brings Polar Pacific or Polar Continental air into the west Gulf States. Sometimes, the polar air which has had 60 to 72 hour over the Gulf, invades the Southern States aloft. In this case, a wave has formed in the Gulf and the weather experienced will be that of a typical warm front character. Sometimes, the polar air is Polar Pacific and at other times, Polar Continental. Regardless of the origin, the weather conditions will be similar to that discussed in paragraph 77. Frequently, $_3$RPpo, $_3$RPco, or Tg air moves into the Gulf States as a very ill-defined front. Many of the usual criteria for determining fronts are not significant in this case, yet a definite movement of a warmer, moister air mass on the continent is noticeable.

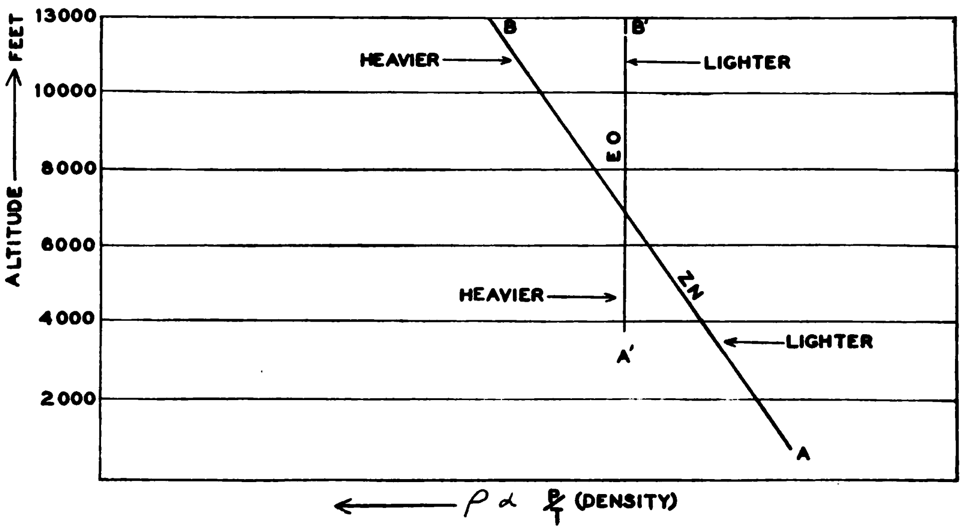


FIGURE 116.—Density curve.

The rapid recession of the old Pp or Pco air formerly occupying the area allows the Tg to run in at the surface without the typical warm front clouds and precipitation.

(1) *Development of situation.*—This situation usually occurs with a polar air occupying the Southeastern States and the anticyclonic circulation bringing $_3$RPpo air with at least 72 hours over the Gulf into Texas. The movement of the High eastward develops a trough along the eastern slope of the Rockies, which aids in intensifying the circulation of the returning air. First indications are a rapid rise in dew point and temperature along the Gulf coast with a shift in winds from E. or ESE. to SE. and SSE.

(2) *Frontal weather.*—(*a*) The clouds are almost always a low stratus. The convergence due to the deepening trough along the Rockies provides the lift needed and the stratus becomes lower and thicker.

(*b*) A heavy mist or drizzle begins before the passage of the front, usually resulting in a dense fog.

(*c*) The ceilings are very low, especially at night. Frequently in the daytime, the front moves by as a dense ground fog, soon breaking and lifting. Ceilings range from zero to 200 feet. Visibilities are usually less than 1 mile.

(*d*) No turbulence will be encountered except in high wind velocities, in which case ceilings and visibilities will improve also.

(*e*) No types of ice will be found.

80. Polar Atlantic—Tropical Atlantic (PA–TA) **in winter.**—*a.* The heavy snowfalls occurring in New England are usually caused by the overrunning of tropical air over a stagnant polar air mass. In many cases, the polar air is a stagnant body of Pc air covering the New England States and eastern Canada. However, the Pc air in the New England States is often modified by passage over the North Atlantic and rapidly attains the characteristics of PA air. The situation develops somewhat as follows:

(1) A cyclone has moved across the Central States, and upon reaching the east coast, deepens and accelerates.

(2) The Pc anticyclone has stagnated over eastern Canada and is feeding PA air into New England and the Middle Atlantic States.

(3) The deepening cyclone draws a tropical air current northward into the New England States.

b. The area of frontogenesis extends along the east coast with the area of cyclogenesis found near Cape Hatteras, N. C.

c. The PA–TA warm front is oriented in a northwest-southeast direction off the east coast.

d. The associated cyclone moves slowly to the NE., occluding rapidly. The warm front moves very slowly. The situation develops rapidly and remains active for several days.

e. The PA–TA or Pc–TA warm front, regardless of the situation, has the following type weather associated with it. Flying conditions with this front are usually quite dangerous, due to the large area affected and the bad weather associated with it.

(1) Cloud forms are stratiform. The extensive cloud system often extends up to 20,000 feet or higher. The cloud system consists of layers.

(2) The precipitation is widespread and of moderate to heavy intensity.

(3) Ceilings usually range from zero to 500 feet with correspondingly low visibilities.

(4) Because of the flat slope of the front, turbulence is not marked.

(5) Severe icing will be encountered.

f. The PA–TA cold front rarely affects the continent. Its area of greatest activity is found in the Middle Atlantic.

81. Polar Pacific—Tropical Pacific (PP–TP) **in winter.**—Normally the path of the migratory cyclones in the North Pacific lies along the 40th to 45th parallel of latitude. When these disturbances move southward or develop in intensity, TP air is forced northward. Usually there exists a mass of stagnant PP air which has been cooled and stabilized by the cold surface and has been prevented

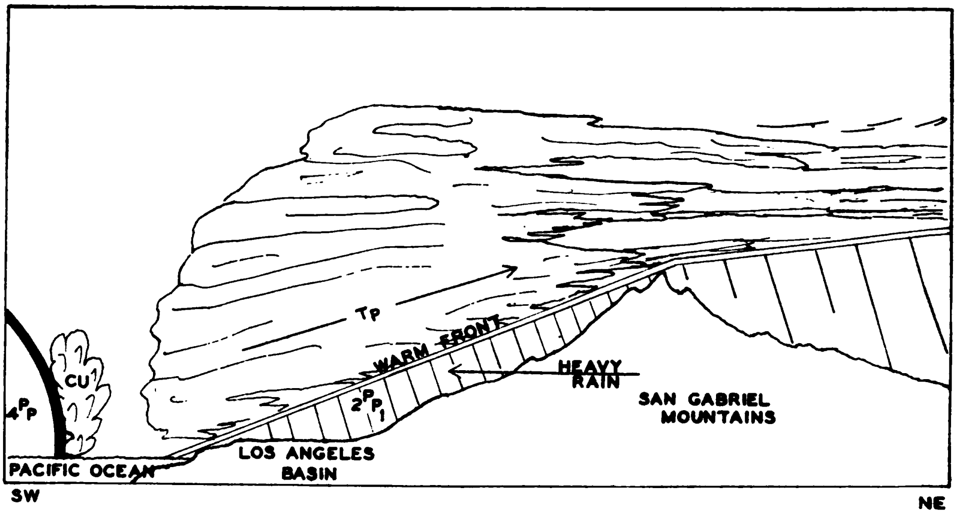


FIGURE 117.—PP–TP warm front in winter.

from moving eastward by the mountain ranges. In this case, California and the west coast experience their heaviest rain falls. The floods which occur in the Los Angeles area every few years are caused by the overrunning of this moist air.

a. Frontogenesis occurs along the west and northwest edges of the Pacific anticyclone.

b. The front usually extends in a north-south direction.

c. In the TP–PP warm front.—(1) Due to the stability of the TP air the cloud forms will be of the stratus type. Upper and lower cloud systems will be pronounced. Flights can be made between the cloud layers. Cloud systems will be extensive and will extend to high levels.

(2) If the front is active and if sufficient lift is provided by the front or by the mountains, a steady drizzle type rain will occur. The amount of rain will be large.

(3) Ceilings and visibilities will be very low, less than 500 feet and

2 miles in the immediate frontal zones. However, ceilings and visibilities 75 to 100 miles ahead of the front or on the leeward side of the mountain ranges will be ample.

(4) Icing will be negligible in warm front clouds due to the warmth and stability of the air. Clear ice will form over higher mountain ranges and in Washington and Oregon, but will not be severe.

d. In the Pp–Tp cold front.—The mountain ranges trap the stagnant polar air and cause the warm front to become stationary. The process of occlusion proceeds very rapidly. The fresh polar air moves southward forcing the tropical air aloft. The Pp–Tp cold front will have the following characteristics:

(1) Cloud forms will be cumuliform.

(2) The precipitation will be in the form of showers. Due to the stability of the Tp air, most of the activity will be limited to the polar air.

(3) Ceilings and visibilities along the front will be low, ranging from 1,000 to 500 feet and 1 to 3 miles. These conditions improve rapidly with the passage of the front.

(4) Considerable turbulence will be found in the unstable Pp air behind the cold front.

(5) Clear ice is found along the front and in Pp air along higher mountain ranges.

e. The polar air which is trapped by the mountains is cooled by the surface and will be colder than the more recent maritime air. This fresh Polar Pacific air will therefore be forced aloft in most cases and will proceed eastward as an upper cold front. This type front yields larger quantities of precipitation and makes flying conditions in the Rockies very hazardous.

f. Occasionally, during the winter, an intense low pressure center will develop in the Great Basin. The deepening cyclone will draw Tp air into the Rocky Mountains. Usually the air at the surface is Polar Pacific, but sometimes Pc air occupies that region. The Tp air is forced aloft, overrunning the polar air and causing heavy precipitation over the entire area. Flying conditions will be extremely hazardous. Ceilings and visibilities will often be below the minimum for contact flying.

82. Polar Pacific—Returning Polar Pacific (Pp–RPp).—A majority of the fronts found along the west coast are those fronts separating a Polar Pacific air mass from a Returning Polar Pacific air mass. This is especially true in the more northerly latitudes. Any tropical air involved in the system will have been forced aloft by the time the front reaches the west coast. Properties of an air mass

having 4 or 5 days over the more southerly latitudes will be different from properties of an air mass with 1 or 2 days over the North Pacific.

a. Frontogenesis occurs in the western and central Pacific. Frontolysis occurs along the west coast.

b. The Pp–RPp front forms on the west and northwest edge of the Pacific anticyclone. The axis of the front will depend on the position of the axis of the High, but is usually southwest to northeast in the central Pacific, becoming west to east along the coast.

c. RPp air is modified by movement over southerly latitudes and is similar in many respects to Tp air. Therefore, the weather expected

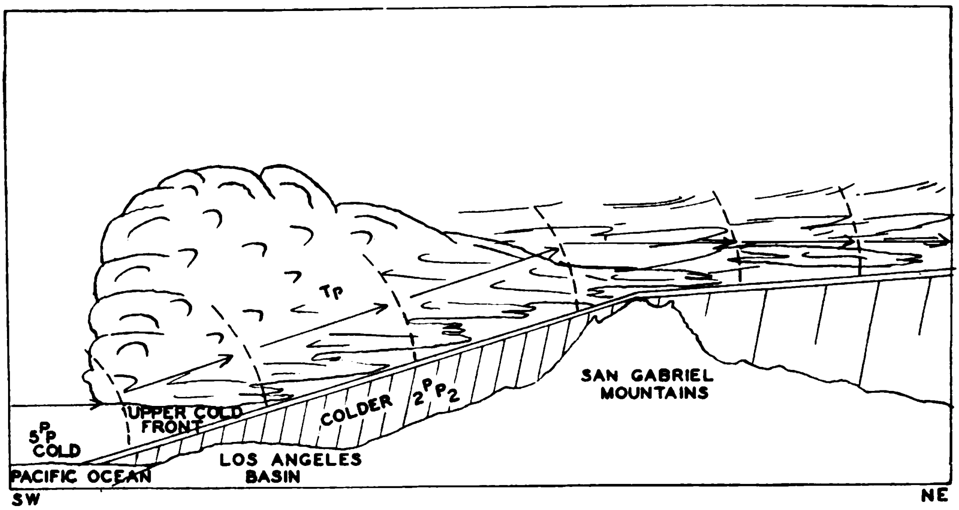


Figure 118.—Pp cold front moving aloft as an upper front over western mountain ranges.

with Pp–RPp warm and cold fronts will be like that found in conjunction with Pp–Tp fronts with the following exceptions:

(1) There is less moisture in RPp air, therefore less precipitation and less activity.

(2) RPp air is less stable, therefore showers and more turbulence.

(3) RPp is colder, therefore more danger of icing.

(4) Ceilings will be higher, as an average, but remaining very low in precipitation.

83. Tropical Continental—Tropical Gulf (Tc–Tg) **in summer.**—*a.* The Tropical Continental air mass originates in the Southwestern United States, is dry and hot, and exists as an air mass only in summer. Frequently it moves eastward and encounters Tropical Gulf air. Very little weather is associated with this front. Clear skies with unlimited ceilings and visibilities prevail. Occasionally the convergent flow along the frontal zone will be sufficient to produce a few scattered thunderstorms.

b. With a semistationary TG—Tc warm front in west Texas, southwesterly winds aloft in central Texas will cause frequent thunderstorms along the front. A majority of the thunderstorms will occur on the windward side of the higher mountain peaks. However, thunderstorms of sufficient intensity do develop sufficiently to cause poor flying conditions in limited areas. Generally, cancellation of flights will not be necessary.

SECTION X

NORTH AMERICAN DRY FRONTS

84. General.—Dry fronts are those fronts which separate the drier or continental air masses. The principal dry fronts are as follows:

Pc–Pp (east of the Rockies)
Pc–Pb
Pc–Tc

These fronts are of less importance to the pilot than the moist fronts and in most cases provide few hazards to flying. However, hazardous conditions do arise, as discussed in paragraphs 85, 86, and 87.

85. Polar Continental—Polar Pacific (Pc–Pp) **in winter.**—Due to the source regions and trajectory of the Polar Continental and Polar Pacific air masses, if these two air masses should approach each other, a front will develop. This front will be either warm or cold, depending on which air mass is the active one. The intensity of the activity in the frontal zone depends upon those properties of the air masses discussed in sections VII and VIII.

a. The descending westerly current of Pp air and the easterly or southeasterly current of Pc air converge along the eastern slope of the Rockies forming an area of frontogenesis.

b. The Pc–Pp front usually extends in a north-south direction and is found east of the Rockies most of the time.

c. In the Pc–Pp warm front, with a deep mass of Pc air occupying the Middle West—

(1) The westerly current of moist Pp air will overrun.

(2) The cloud forms will be of the warm front type.

(3) A general blizzard condition will exist with heavy snow.

(4) Ceiling will be very low, usually less than 500 feet. The visibilities in frontal zones will be usually less than 3 miles and zero in precipitation.

(5) Icing conditions exist with rime ice being found in the Pc air and clear ice being found in the Pp air.

d. With Polar Pacific air occupying the Middle West, a Polar Continental air moves southward with the more dense Pc air displacing the Pp air as a cold front. The Pp air is usually so stable and dry that little activity results.

(1) The cloud system associated with the front is not extensive and is usually found in the Pc air.

(2) Precipitation is in the form of light snow flurries.

(3) Ceilings are 800 to 1,000 feet, dropping to less than 500 in snow. Visibilities will be greater than 3 miles except becoming zero in snow flurries.

(4) Turbulence will be encountered only with excessive wind velocities.

(5) Icing will be of a rime character with a slight possibility of clear ice formation in turbulent air.

86. Polar Continental—Polar Basin (Pc–Pb) **in winter.**—At infrequent intervals during the winter, the Great Basin anticyclone moves eastward, and as it descends the eastern slopes of the Rockies, it frequently comes into contact with Polar Continental air. As in the case of descending Pp air, the "foehn" effect or adiabatic heating results in the formation of a warm front.

a. The area of frontogenesis or development of the front is along the east slope of the Rockies.

b. The axis extends in a N-S direction.

c. The situation develops very rapidly with a deepening of the associated cyclone.

d. The Pc–Pb warm fronts have very little weather connected with them.

(1) The clouds are usually the high type, with cirrus or altostratus predominating.

(2) Precipitation will not ordinarily be found with this front.

(3) Ceilings and visibilities will remain very good.

e. Pc–Pb cold fronts are of little importance except where dust storms and turbulence occur. The dust storms occur in the same manner as those associated with Pp cold fronts.

87. Tropical Continental—Polar Continental (Tc–Pc).—The Tc–Pc front or Tc–Pp fronts are seldom marked by any weather at all. These fronts are very weak and are usually characterized by a few

altocumulus and no precipitation. Moderate turbulence will be encountered, especially in the lower levels in the afternoon. These fronts occur only in summer.

SECTION XI

FORECASTING

Paragraph

88. Necessity for weather training.—*a*. The ultimate goal of the Air Corps Weather Service is to train Air Corps pilots and forecasters so that they will be able to make accurate flying forecasts. The forecasters realize this well enough but there is a tendency on the part of pilots to fail to supplement what they learn from a forecaster with what they hear and what only they are in a position to see regarding the weather while they are in flight. Commanders of aircraft cannot evade the responsibility of making decisions in regard to the weather.

b. The material in this manual is presented from a dual standpoint; that of the commander of aircraft and that of the forecaster. The single aim is to aid the pilot in the efficient performance of his mission. To accomplish this prime purpose of all military flying in both peace and war, the weather must be considered. Modern weather analysis has opened avenues of approach to what has previously often been an unpredictable and unfathomable phenomenon—the weather. The pilot should be trained so that he will have reasonable confidence in his own decisions and in the information given him by the forecaster. It is believed that this may be accomplished by teaching him the basic principles of air-mass analysis together with some of the more detailed technique used by the forecaster.

c. All pilots should be able to read a weather map intelligently. It displays a tremendous amount of information in a pictorial manner, and a brief survey of it, guided by a forecaster, will reveal in a few moments what it would take hours to describe accurately. Weather,

like all other subjects, has a language of its own and unless the pilot understands this language, which is rapidly being assumed by the forecasters, he will not have the proper background for any decisions he may be required to make.

d. There are many other reasons why all Air Corps officers should have as thorough a knowledge of the weather as it is possible for them to attain. The most personal is that it is one of the best forms of life insurance a pilot can possess. It is a curious fact that in spite of the advances in flying training, equipment, aids, and weather knowledge, the death rate in the Air Corps has remained almost constant for a period of years. Types of weather are being safely flown through now that it would have been impossible to negotiate a few years ago, but it will always remain a hazard that will be pushed closer and closer to the limit in order to fulfill the purpose of all military training—success in battle.

e. The subject of the use of weather as a tactical aid is just beginning to be recognized. It is of paramount importance and will only be outlined here. It has recently been introduced at the Air Corps Tactical School and is gradually being considered at the higher military schools of this country.

f. Air Corps policy prescribes that weather officers will remain in the weather service for a period of 4 years. This means that they will be learning how to predict the weather during a large portion of their tour of duty as weather officers, and even at the end of 4 years they will be far from infallible. One of the world's most renowned and expert forecasters says, "In order to be able to forecast the weather with reasonable accuracy, it is necessary to have a thorough knowledge of the physics of the atmosphere, several years' experience in general forecasting, and also a thorough knowledge of the numerous local influences due to terrain." It is doubtful if anyone has ever seen any two weather situations that were exactly alike.

g. The vast majority of forecasters in the weather service are enlisted men. Their term of enlistment is for 3 years. Great effort is being made to retain them in the service, but they are being lost continually to other agencies. They do not have the theoretical and practical background that the weather officers have. Their flying experience is limited, and flying experience is essential to a forecaster making flying forecasts. Many landing fields used by the Air Corps do not now and never will have a forecasting service.

h. One prime reason why forecasts will never be perfect is that no one will ever know the exact state of the atmosphere; the problem is too great, complex, and changes too rapidly. The meager upper-air

and surface data are not sufficient to complete the picture; for example, no soundings are made between Salt Lake City and El Paso, a distance of over 600 miles. It cannot be repeated too often that the pilot's position in this respect is unique in many ways. The position of the forecaster might be compared to that of a doctor; an expert diagnostician is rare because the required information is often hidden within the human body.

89. Forecasting procedure.—*a*. There are three main steps for the pilot to follow in arriving at a decision:

(1) Get and keep in mind a complete picture of the current weather situation.

(2) Move this picture forward in space and time to cover the time and route of flight.

(3) Consider the changes that will occur during the time in the air.

b. The forecaster should follow the same procedure as in *a* above only in a more detailed manner. The three basic elements in the preparation of a forecast are as follows:

(1) *Physical analysis.*—This requires a knowledge of all of the thermodynamical characteristics of the various air masses and use of this knowledge to explain the existing weather. Construction of the weather map, supplemented by teletype, pilot, and radio weather reports, and local observation are the means used to obtain a complete understanding of the current weather.

(2) *Extrapolation.*—This is the projecting forward in time and space of the existing activities in the atmosphere. It is best done by kinematic methods which take into consideration the direction and velocity of the wind, the movement of pressure systems, convergence, divergence, vertical velocities, curl, and movement of fronts.

(3) *Physical changes occurring during the forecast period.*—This involves frontogenesis, frontolysis, time of day, season, terrain, and other factors which affect the properties of air masses and the activity of fronts. This is perhaps the most difficult element of a forecast to give proper consideration.

90. Physical analysis.—*a*. The pilot gets his picture of the current weather from the forecaster, a study of the weather map, teletype and radio weather reports, and from what he sees. At times when no forecaster is available, he must make his own analysis from available data. It is possible at any one place to draw a weather map of a comparatively large area from broadcast weather reports. Some pilots carry portable radio receivers which may be used for this purpose. At the smaller Air Corps weather stations, a weather map may be available although no forecaster or only a student forecaster

is on duty. The same situation may be true at some Weather Bureau stations at civilian airports.

b. Air Corps weather maps are drawn by weather officers, enlisted forecasters, and enlisted student forecasters. One of these maps is drawn every 6 hours at base weather stations and at less frequent intervals at the smaller stations. Weather maps are drawn with a series of previous maps displayed before the forecaster. A satisfactory weather map can only be drawn when the forecaster has a knowledge of previous weather. Probably 50 percent of the value of a forecast depends upon whether there has been a correct determination of the life history of the air masses and the movement of fronts and centers. The construction of a weather map may be divided roughly into the following steps:

(1) Plot reported weather data.

(2) Study the past weather and extrapolate it forward to the time of the current map.

(3) Sketch in the positions of the fronts on the map being drawn. This may be done directly or by first lightly drawing isobars, one for each third millibar, in the frontal zones. The location of fronts is often difficult and should be done with great care using all the available criteria, such as history, pressure distribution, cloud systems, and winds. The simple rule that a front must lie in a pressure trough combines the two important factors of reliability and ready use.

(4) Using the principles described under "Isobaric analysis" in the appendix, draw the isobars as heavy lines with a soft pencil. They should fit the winds and reported pressures, the allowable error usually being about 0.8 millibar. Indicate the value of each isobar at the point where it leaves the map, also the value of center isobars.

(5) Color the fronts, precipitation areas, past positions of fronts and centers, and label the air masses, centers, and aviation hazards such as thunderstorms, dust, and fog.

(6) Sketch in the isallobars which show the changes that will take place in the pressure field.

(7) Indicate the direction of motion of centers and determine the movements of fronts and centers during the forecast interval. It is desirable to indicate the future positions of fronts. Drawing the future map is an excellent aid to forecasting that is now being used in some places.

91. Movements of weather.—*a.* When the current weather has been analyzed, the next step is to extrapolate forward in space and time. If the forecast interval is short (3 to 6 hours), it is often possible to use the past history to determine the amount of motion that will

take place. For a longer-range forecast, extrapolation from past history alone is a great aid but should be supplemented by determinations of velocities and accelerations made from the current weather map. The intensity of weather systems varies with time, and changes in intensity cannot always be obtained by simple extrapolation.

b. Petterssen has developed rules, based upon various relations of the field of pressure, which offer the best solution to the problem of determining future movements, accelerations, and the changes in intensity of the pressure systems. Due to the close relation between air currents and pressure distribution, it is advantageous to study the movements of the pressure systems instead of the air particles or air masses themselves. For example, when we have determined the

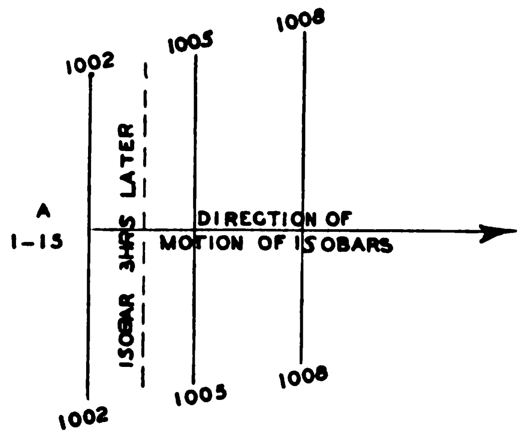


FIGURE 119.—Movement of an isobar.

movement of a cyclone and the fronts associated with it, we will also know the large-scale movement of the air masses. It is also useful to find out the movement of centers of high pressure (anticyclones). He has expressed these rules in terms of pressure only, because atmospheric pressure is the only element for which no question of representativeness arises. These rules were developed through the use of rigorous mathematics, chiefly the calculus and differential equations. They are used in the Air Corps Weather Service and throughout the world wherever weather forecasting is done.

92. Movement of isobars.—*a*. Before discussing the movements of pressure centers or fronts, the movements of isobars will be examined because they are the basic element of these systems as portrayed on the weather map. Assume that the isobars are distributed as shown in figure 119 and that it is desired to calculate their displacement during the forecast interval.

b. The variations, or the changes in the pressure distribution from one chart to another, depend upon the barometric tendencies. Having

the pressure tendency at the point A on the 1002 isobar, its displacement along an axis perpendicular to the isobar can readily be determined. Since the tendency at A is —1.5, the pressure at A was 1003.5 3 hours ago. Since the pressure at A has dropped 1.5 during the last 3 hours, the 1002 isobar will be displaced toward isobars representing higher pressure. Such a movement must take place, for with the same drop in pressure during the next 3 hours, the barometer at A would read 1000.5. Assuming the same drop would occur all along the 1002 isobar, it would be moved to a point half-way between its present position and the present position of the 1005 isobar. This example serves to illustrate the following rule: The normal velocity of an isobar is equal to minus the local pressure tendency multipled by the distance between neighboring isobars. In order to use this equation correctly, the following facts must be considered: first, pressure tendencies are given in tenths of a millibar while unit isobars are drawn for every 3 millibars; second, the normal period for measuring pressure tendencies is 3 hours so that velocities derived from this formula will be expressed in terms of this unit and whatever unit is used to measure the distance between isobars. Finally, falling tendencies will give positive velocities or movement toward higher valued isobars, and rising tendencies will give negative velocities or movement toward lower valued isobars. The velocities calculated are always directed along an axis perpendicular to the isobars.

c. The above analysis gives the instantaneous velocity of the isobar under consideration. Consequently, to obtain accurate results, the pressure tendency must remain constant during the forecast interval. These ideal conditions rarely exist for extended periods of time with the result that forecasts for longer than 24 hours usually become inaccurate in detail because of acceleration. Complex formulae do exist for calculating the acceleration of an isobar and pressure systems. However, since accelerations are usually small during 24-hour periods, such formulae are omitted.

d. Calculation of the movement of isobars is very helpful in forecasting wind velocity and direction. Figure 120 taken from Petterssen's paper, "The Kinematical and Dynamical Properties of the Field of Pressure with Application to Weather Forecasting," shows the accuracy with which a forecast of wind direction and velocity may be made by use of the formula for the velocity of an isobar. He says, "The first map in figure 120 gives the pressure distribution and wind observations over west Norway on the 12th of January, 1932, at 1900. The second map gives the observed pressure distribution and the observed winds 18 hours later, and the third map gives the pressure

distribution calculated 18 hours ahead. It is seen that the pressure gradient agrees well with the calculations and that a wind forecast, based on the calculations of the future pressure distribution, would have given the observed wind velocities. The actual forecast for the 13th was SSE. 9 to 10 Beaufort. The forecast was founded on calculations."

93. Movement of pressure centers, troughs, and wedges.—*a.* The motion of a pressure center (low or high) along any chosen axis may be obtained from the following equation by simple arithmetic:

$$\frac{1}{2}\,\frac{T'-T''}{(p-p')+(p-p'')}$$

where T' and p' are the tendency and pressure, respectively, at a convenient unit's length ahead of the center (usually about 300 miles)

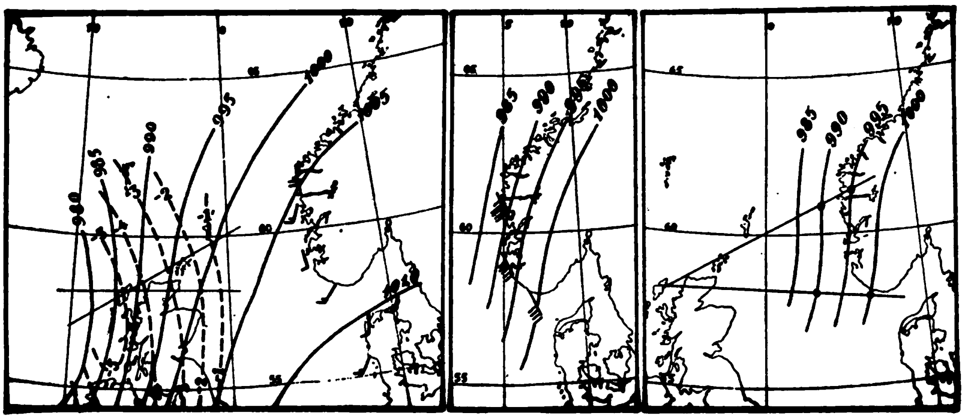


FIGURE 120.—Comparison of actual and calculated movement of isobars.

along the axis, T'' and p'' are the same quantities at a similar distance in rear of the center and p is the pressure at the center. The result will be the movement in terms of the unit length chosen for a 3-hour period. To obtain the amount of movement in the selected direction for longer periods, multiply by the appropriate number; for example, to get a 24-hour movement, multiply by 8. This formula neglects accelerations but is usually reasonably accurate for 24-hour displacements. If the axis has been chosen in the direction of motion, the initial result will give the total movement of the center; if not, it will give the component along that axis. In the latter case it is necessary to calculate the motion along some other arbitrarily chosen axis, then construct perpendiculars to the two axes at the ends of the components for time period selected. The intersection of these perpendiculars gives the point that the center will reach at the end of the fore-

cast interval. The two restrictions on the use of this formula are that the unit length should be as long as possible with a fairly uniform pressure gradient along it, and that the axes cannot cross a front. This latter restriction sometimes makes computations difficult with cyclones.

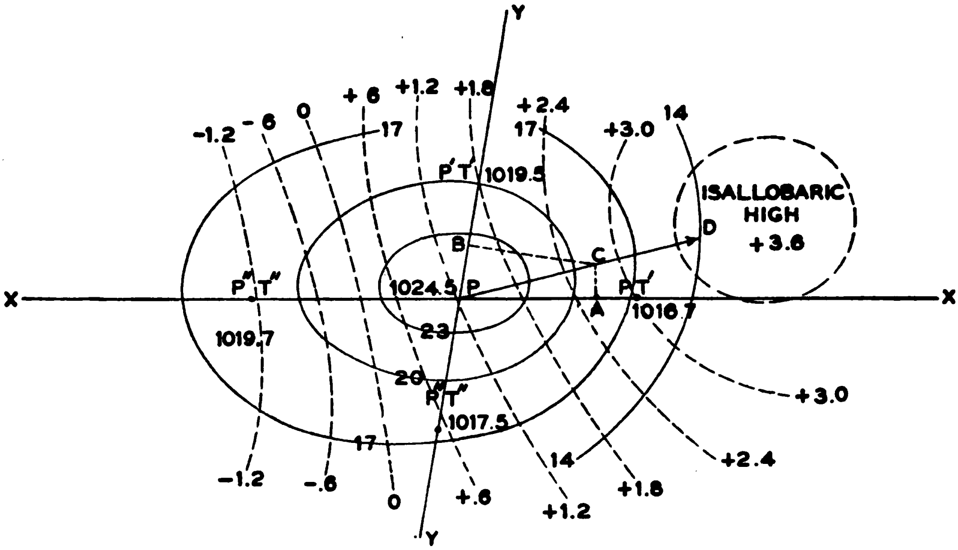


FIGURE 121.—Use of center formula.

$$\text{3 hr. displacement along } x \text{ axis} = \frac{1}{2}\,\frac{3.0-(-1.2)}{(1024.5-1016.7)-(1024.5-1019.7)}$$

$$=\frac{1}{2}\,\frac{4.2}{7.8+4.8}=\frac{2.1}{12.6}=\frac{1}{6}$$

$$\text{12 hr. displacement} = 4\,\frac{1}{6}=\frac{2}{3} \text{ of unit length (to point } A\text{)}$$

$$\text{3 hr. displacement along } y \text{ axis} = \frac{1}{2}\,\frac{1.8-(+.6)}{(1024.5-1019.5)-(1024.5-1017.5)}$$

$$=\frac{1}{2}\,\frac{1.2}{5.0+7.0}=\frac{.6}{12.0}=\frac{1}{20}$$

$$\text{12 hr. displacement} = 4\,\frac{1}{20}=\frac{1}{5} \text{ of unit length (to point B)}$$

b. In figure 121, perpendiculars were erected at *A* and *B* which intersect at *C*, the position of the center at the end of 12 hours; the movement was doubled and the new position *D*, at the end of 24 hours, was obtained. This formula may be used to calculate the movement of pressure troughs and wedges. The axis is drawn perpendicular to the long axis of the trough or wedge and the movement is calculated in axial direction only.

c. The above formula and other considerations have led to the following rules concerning the movement of pressure centers:

(1) Cyclonic centers move in the direction of the warm sector isobars. This is the simplest and most easily applied rule with the accuracy that it gives and consequently is used constantly. (See fig. 122.)

(2) Very oblong centers move along the longest symmetry axis. (See fig. 122.)

(3) Cyclonic centers move in the direction of the isallobaric gradient. (See fig. 122.)

(4) Anticyclonic centers move in the direction of the isallobaric ascendant. (See fig. 121.)

(5) Pressure centers whose profiles are steep move slowly. Young cyclones rarely have steep pressure profiles and therefore move

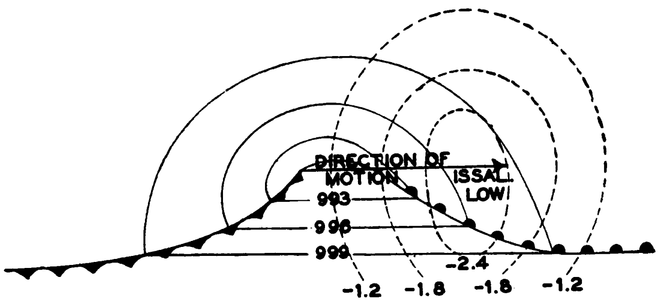


FIGURE 122.—Movement of a cyclone.

more rapidly than older cyclones. Deep cyclones sometimes recurve because of the steep pressure gradient they cause ahead of themselves. (See fig. 123.)

d. The following examples in figure 124 showing the calculated and actual movement of eight pressure centers have been taken from Petterssen's paper:

"Full lines observed paths. Broken lines paths computed from the writer's formulae. Dotted lines paths computed by means of Angervo's formulae. All paths are calculated 24 hours ahead and the positions corresponding to the intermediate weather charts are indicated.

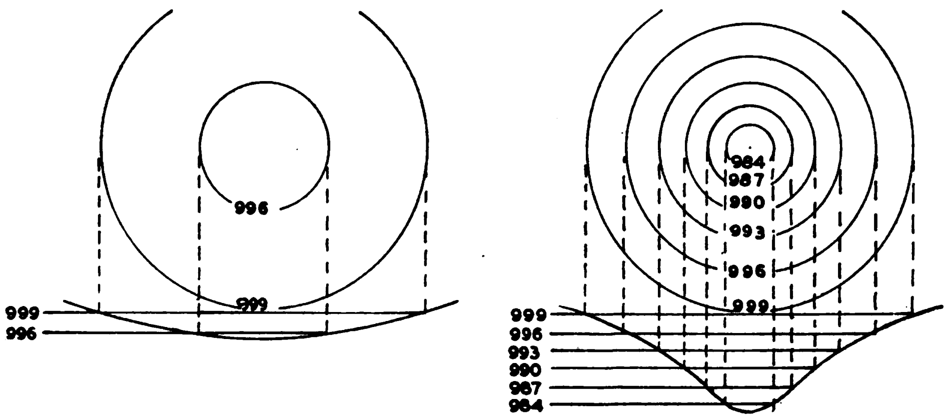
"It is seen from the maps that the agreement between the computed and the observed paths on the whole is good. No. 1 exhibits a considerable discrepancy which was caused by the approach of a secondary perturbation. In view of the fact that it is not always easy to locate the position of a pressure center with larger accuracy than 50 to 100 kilometers, the discrepancies in the above example are insignificant.

"It is seen from the above examples that the accuracy obtained is as large for quickly running centers as for slowly moving ones."

94. Movement of fronts.—*a.* The displacement of fronts may be obtained from the following formula:

$$\text{Displacement of front} = \frac{T_A - T_B}{(p-p') + (p-p'')}$$

where T_A is the tendency immediately ahead of the front and T_B is the tendency immediately behind the front. In figure 125 the isallo-



① "Flat" center, may move rapidly. ② Steep profile, will move slowly.

FIGURE 123.

bars behind the front have been extrapolated up to the front from the previous 3-hour position of the front.

b. From the front formula it is seen that the velocity of a front is directly proportional to the tendency differential across the front and inversely proportional to the steepness of the pressure profile. Rapidly moving fronts have flat pressure profiles with tendency differentials of some magnitude while slowly moving fronts have steep pressure profiles.

The calculations are—

$$3\text{ hr. movement} = \frac{-1.8-(+2.7)}{(4.0-14.0)+(4.0-6.0)} = \frac{4.5}{12}\text{ (to A)}$$

$$24\text{ hr. movement} = 8 \times \frac{4.5}{12} = 3\text{ units}$$

c. Cold fronts move with a velocity of 80 to 100 percent of arm geostrophic wind behind and perpendicular to the front, and womfronts move with a velocity of 60 to 80 percent of the similar component.

Petterssen gives the following example in figure 126:

"A front which on the 12th of March 1932 at 8 M. E. T. had passed the west coast of Norway. The same morning there was no pressure gradient over the Baltic. The wind everywhere was slight. The

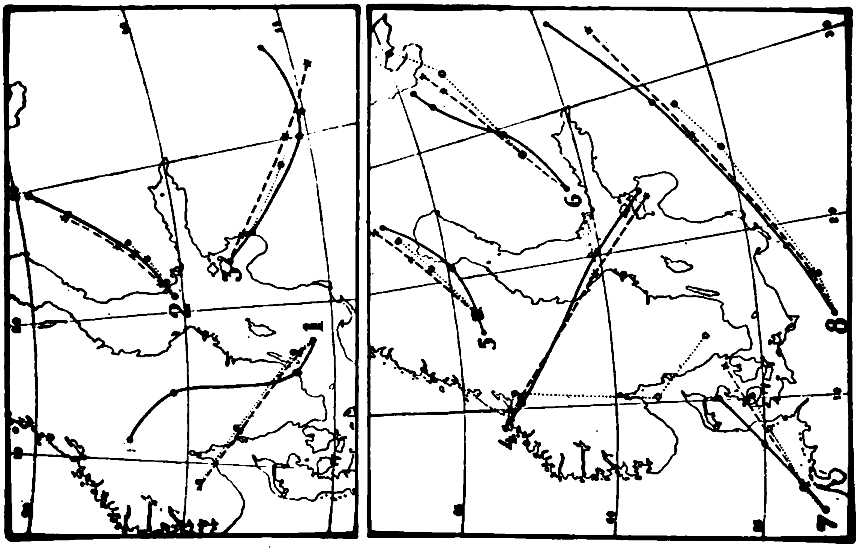


FIGURE 124.—Calculated and actual movement of pressure centers.

velocity of the front was calculated for two points indicated by arrows on the chart. The displacement was computed to 19 M. E. T. (the broken line). The agreement was perfect.

"In order to see what winds were likely to occur over the Baltic area, the velocity of the isobars was calculated. (Accelerations were

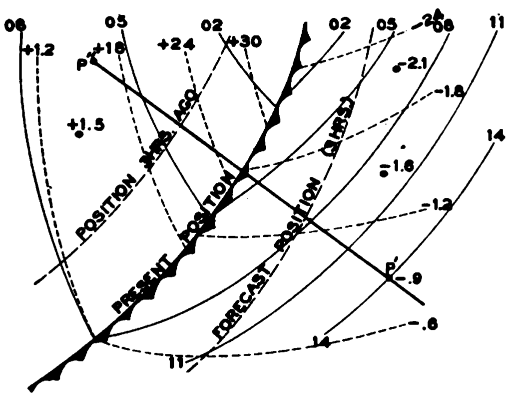


FIGURE 125.—Movement of a front.

not obtainable.) The computed isobars at 19 h. are given on the map and the winds observed at 19 h. are plotted."

95. Deepening and filling.—*a.* By the "deepening" of a pressure center, trough, or wedge is meant a decrease in this value of the pressure in the center, trough, or wedge. "Filling" means the reverse

process is taking place. A "wedge line" or "trough line" is the line perpendicular to the isobars in a trough or wedge, and it usually is a line of symmetry.

b. Since the pressure in the center of a HIGH or LOW is either greater or less than the pressures surrounding it—

(1) The deepening or filling of a HIGH or LOW is proportional to the tendency at the center.

(2) Lows and troughs deepen when the tendencies at the center along the trough line are negative after the tendency due to movement has been subtracted. They fill when the tendencies at the center or along the trough line are positive after the tendency due to movement has been subtracted.

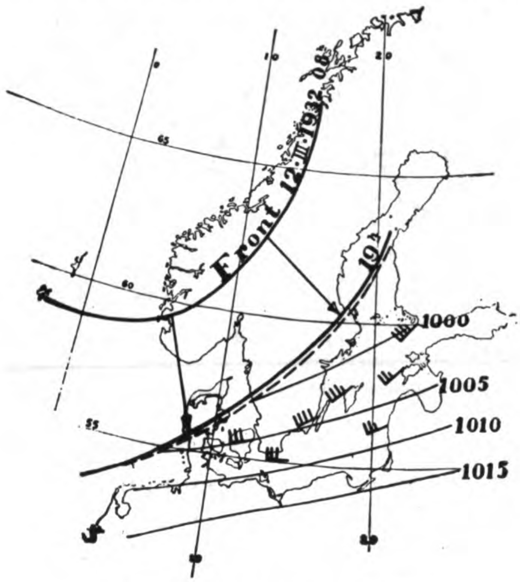


FIGURE 126.—European example.

(3) HIGHS and wedges fill (increase) when the tendencies at the center or along the wedge line are positive after the tendency due to movement has been subtracted. They deepen (decrease) when the tendencies at the center are negative after the tendency due to movement has been subtracted.

96. Changes of intensity.—The deepening of a center does not necessarily mean an increase in the intensity of circulation, for the deepening may occur over a wide area and cause no change in the spacing of the isobars. Since the geostrophic wind is a function of the spacing between isobars, changes in intensity are shown by changes in this spacing. Practice with the formula for the velocity of an isobar will make it possible for the forecaster to readily determine by

inspection whether the isobars are going to come closer together or whether they will spread apart. (See fig. 120.)

97. Occlusion of waves.—The rate of occlusion may be determined from the relative velocities of the cold and warm fronts in a wave. The rate of occlusion may also be determined from the following simple rules:

a. If the warm sector tendency is negative, the cyclone will tend to occlude rapidly.

b. If the warm sector tendency is positive, the cyclone will be relatively stable with little or no occlusion.

98. Deflection of winds.—*a.* "Cyclogenesis" means the formation of, or the strengthening of, a cyclone. "Anticyclogenesis" means the formation of, or the strengthening of, an anticyclone. Winds are deflected by the formation or strengthening of these systems in accordance with the following rules:

(1) The winds are deflected from the isobars in proportion to the cyclogenetical intensity.

(2) The winds are deflected from the isobars in proportion to the anticyclogenetical intensity.

b. It is during the processes of cyclogenesis and anticyclogenesis that the weather changes most rapidly over large areas. These factors are often difficult to determine but a careful examination of the barometric tendencies will reveal them. When the tendencies have relatively large values and show a decrease and then an increase along a given line, cyclogenesis will take place; if they show an increase and then a decrease, anticyclogenesis will take place.

c. The use of the above equations and rules has contributed in a large measure to the remarkable accuracy that is frequently obtained in flying forecasts. These methods combined with extrapolation and the use of the geostrophic wind will give reasonable accuracy for forecasts of the movements of the weather systems.

99. Changes during forecast interval.—When the approximate displacements of the pressure systems, fronts, and air masses have been determined, the next step in the preparation of a forecast is to determine what physical changes will occur during the period covered by the forecast. Some of the significant changes in the weather during relatively short periods of time are listed under the chief means by which they are effected:

a. Trajectories of air masses over a warmer or cooler surface.—(1) Fog and low stratus over snow and much cooler water or land at night.

(2) Cumuliform clouds, scattered showers, and thunderstorms over warmer surfaces as when going from water to land in summer and land to water in winter.

(3) Gustiness and turbulence over warmer surfaces.

(4) Development, dissipation, lifting and sinking of icing zones.

b. Diurnal heating and cooling.—(1) Formation of fog and low stratus at night with dissipation in the morning. Fluctuation of ceiling and visibility.

(2) Cumuliform clouds and bumpiness over land during the day and stratiform clouds with smooth air at night. The reverse is true over the ocean.

(3) Showers and thunderstorms in the afternoon that may last until late at night.

(4) Lifting of icing zones in the lower levels during the day with sinking of them at night.

c. Local topographic effects (orographic effects).—(1) Strong winds and severe turbulence through mountain passes from rapidly moving pressure systems.

(2) Rain, showers, thunderstorms, stratiform and cumuliform clouds, and low ceilings and visibilities due to sudden lifting of damp and sometimes conditionally unstable air.

(3) Local dust storms from strong winds.

(4) Rapid clearing on leeward side of mountains in strong winds.

(5) Formation and dissipation of low fog and stratus along shore lines.

(6) Retardation and deformation of fronts by mountains.

d. Frontogenesis and frontolysis.—(1) Transition from inactive to active fronts in areas of frontogenesis. The exact location of where an inactive front will become an active one is often very difficult for the forecaster to determine but if the pilot is cognizant of the possibilities of the situation, he may readily recognize, understand, and evaluate the changes that are taking place along his course.

(2) Transition from active to inactive fronts in areas of frontolysis.

e. Rapidity of changes.—(1) The changes due to the trajectories of the air masses are usually slight during 3- or 6-hour periods. For this reason, it is possible to make flights in the majority of cases of like duration and expect to find the weather at the terminal similar to the terminal weather at the time of take-off. During a majority of the time, the last weather reports received before take-off on 3- to 6-hour flights give a very good indication of what the weather will be at the time of arrival. The factors that cause rapid changes are listed in *a* above.

(2) The effects listed in *b* above are due to the seasons and time of day. They occur more frequently and usually with more rapidity than those listed in *a* above.

(3) Topography may cause rather sudden changes, particularly during periods when the maximum diurnal heating or cooling effects are taking place.

(4) Changes that occur in areas of frontogenesis or when an inactive front becomes an active front may cause large transformations during the time interval. When a dry front changes to a wet front, it does not do it suddenly but over a period of at least a few hours and the observant pilot can see the transformation take place.

100. Summary.—Assuming that the forecaster has made a careful physical analysis, the steps given below should be followed in the preparation of a flying forecast:

a. Determination of displacements of pressure systems including fronts, highs, lows, troughs, and wedges.

b. Determination of deepening and filling.

c. Prediction of formation of new systems; frontogenesis and new waves.

d. Readjustment of displacement of fronts and centers after considering deepening, filling, frontogenesis, and formation of new waves.

e. Determination of the air mass or air masses that will occupy the forecasting district. Make detailed study of properties of these air masses.

f. Determination of changes expected in properties of these air masses.

g. Consideration of local influences such as mountains, oceans, and lakes.

h. Critical reexamination of the entire weather map. Reconsider all possibilities, that is, ask "What can upset my forecast?"

Section XII

FOG AND LOW STRATUS

101. Condensation.—*a.* Many of the various factors concerning the condensation of water vapor in the atmosphere remain partly or entirely unexplained. It is unknown why, at times, relative humidi-

ties of about 100 percent are required for condensed water vapor to become visible, while at other times, condensed water vapor may be seen at relative humidities of less than 50 percent. It appears that the lower the altitude above the surface of the earth, the higher the relative humidity required to produce visible moisture. However, this is not always true, as relative humidities of 100 percent have been observed at high altitudes. Experiment has shown that water vapor will not condense in pure air so it is probable the amount and type of impurities are determining factors.

b. The principal impurities in the air upon which water vapor condenses are the various hygroscopic sea salts such as common salt (sodium chloride, NaCl) and other metallic chlorides and sulphates. The source of these is the sea itself. They are introduced into the air through the action of white caps and breakers in a rough sea. Observation of the hazy appearance of the air near the sea surface on a windy day will verify this. Maritime air masses contain more condensation nuclei than continental air masses and condensation phenomena occur more readily in maritime air masses.

102. Fog.—Fog is any type of condensation that covers the ground; it consists of minute water particles (about 0.001 inch in diameter or less) and restricts the visibility to certain limits.

103. Haze.—*a.* Haze is very fine salt, dust, or smoke particles suspended in the air with none or very little moisture content. They are invisible to the naked eye but have strong effect on distant visibility and coloring. They cause dark objects to look blue and white objects to look yellow. In the distance, all details vanish because of haze. Mountains are made to look like silhouettes. The nearer the air approaches saturation, the thicker the haze becomes. It usually has a grayish appearance which is in sharp contrast with the white of any clouds that may be adjacent. Since maritime air masses attain the greatest amount of salt particles, haze is usually thickest in them. Conversely, arctic air is sometimes called pure air because of its lack of haze.

b. An increase in the thickness of the haze is a good indication that the air is approaching saturation and that fog or clouds may be expected to form. Haze becomes more dense in the vicinity of frontal zones. This is a good indication that a frontal zone is being approached. Along stationary fronts where waves are being formed, the wave areas are usually distinguishable by the thickness of the haze. A succession of haze layers indicates a series of small inversions. Haze usually accompanies the sea breeze and the forward edge of this wind may often be noted by a distinct line of demarca-

tion between hazy air and clear air. When fog is expected in such an area, it will occur in the hazy air and not in the clear air. Consequently, the edge of a haze line, "sea breeze front," is a good indication of the outer limits of any expected coastal fog.

104. Low stratus.—*a.* Low stratus is a low flat cloud. The ceiling beneath this cloud must be at least 50 feet, otherwise it is reported as fog. It is sometimes called, particularly on the west coast, "high fog." It may develop from or into fog and is usually allied with fog conditions. No exact upper limit has been assigned to this type of cloud. Stratus clouds beneath which the ceiling is less than 1,000 feet are usually considered as low stratus. When low stratus exists, the hazards to aviation are similar to those in fog. This point is emphasized by the fact that when the ceiling is below 500 feet, the major airports of this country report the weather as class "X." A class "X" weather report, according to Federal regulations, prevents any landings at that airport. Experienced instrument pilots consider 600 feet as a minimum ceiling through which they may let down with safety.

b. Fog usually lifts under either of the two following influences or a combination of both: An increase in wind velocity sufficient to lift the base of the inversion off the ground, and heating of the ground by the sun sufficient to cause convections. Low stratus may be formed, however, by either of the above methods without the previous existence of fog. At night, when the surface temperature and dew point are near each other, a wind in excess of 12 miles per hour is usually strong enough to establish an adiabatic lapse rate in the lower levels. This brings the temperature and the dew point together at some level not far above the level of the ground and forms low stratus at that elevation as shown in figure 130. The establishment of an adiabatic lapse rate in the lower levels causes convections from the ground to the base of the clouds and an even distribution of moisture throughout this layer. The pilot can recognize such a layer by the bumpiness of the air beneath the low stratus. The stronger the wind the higher the ceiling.

c. After sunrise, insolation adds its effect to the turbulence caused by the winds or, with a clear sky when the temperature and the dew point are near each other at the ground, convections started due to the effect of insolation frequently are sufficient to cause the formation of low stratus. The clouds formed in either of these two cases are not strictly stratus but stratocumulus. It is bumpy within them. They are flat on top when the lapse rate above the clouds is very stable. In warm air masses where the lapse rate approaches the pseudo-adiabatic, the tops may have the appearance of typical stratocumulus,

105. Visibility.—The visibility in fog and haze is variable depending upon the lighting of objects, time of day, and light employed. It is better in the directions away from the sun than in the directions toward the sun and better when the object in view is lighted and the hazy area intervenes than when the intervening area is clear and the object is in a hazy area.

106. Aviation hazard.—Fog, haze, and low stratus have always been hazards to aviation. Instrument flying, radio aids, and celestial navigation have largely solved the difficulty for flying between terminals. Various methods have been invented to make landing possible when the ceilings and visibilities are very low or zero. They require special equipment and training, either or both of which may not be available to the pilot at a critical time. The hazards remain. The best policy is to avoid the necessity for landing at an airdrome where the ceiling and visibility are below safe limits. This requires expert forecasting before take-off and the constant attention of the pilot during his flight. It is a waste of time and material to take off for a given destination and then have to turn back or go to some other airdrome. Such flights are called "attempted flights" and are rapidly diminishing in numbers. It is not always possible to return to the point of take-off because the weather at any given locality does change.

107. Classification.—All fogs and low stratus may be classified in either of the two following groups:

a. *Air mass fogs and low stratus.*—These are fogs and low stratus which occur due to the interactions within a single air mass. They may be further subdivided into radiation, advection, up-slope, and double-inversion types.

(1) *Radiation fog.*—This fog is caused by the cooling to saturation of layers of air due to heat loss by radiation. Fog formed in this manner has been further subdivided into ground fog and high inversion fog.

(*a*) *Ground fog.*—This fog is formed over continental areas by the cooling of air layers adjacent to the ground through two processes. The first of these is the heat loss by radiation from the layers of air themselves. The second and most important is the cooling of the lower layers by contact with the ground. After sunset, the earth cools off more rapidly than the air. The lower layers of air which come in contact with the ground lose their heat and approach saturation more rapidly than those immediately above. This fog first appears as tenuous wisps which gradually spread in extent and increase in density. Cold air being heavier than warm air, it tends to move down slopes into the lowest areas and there is where ground fog

will first begin to form. The pilot should be keenly alert for the first appearance of the thickening haze and the narrow streamers of fog that indicate the formation of a ground fog. The temperature differential between fog and no fog is frequently so slight that an area which originally was clear may be covered by fog within the next few minutes. The ground fog may be only knee deep but still it offers a landing hazard and it soon may become thicker. The visible portion of known objects may be used to give the pilot an estimate of the thickness of the fog. Airplanes have landed in ground fogs but have been unable to taxi to the line because of the rapidly increasing thickness of the fog. Ground fogs occur in light winds, usually less than 8 miles per hour. A little wind is necessary to distribute upward the colder air next to the ground. Since water vapor is the

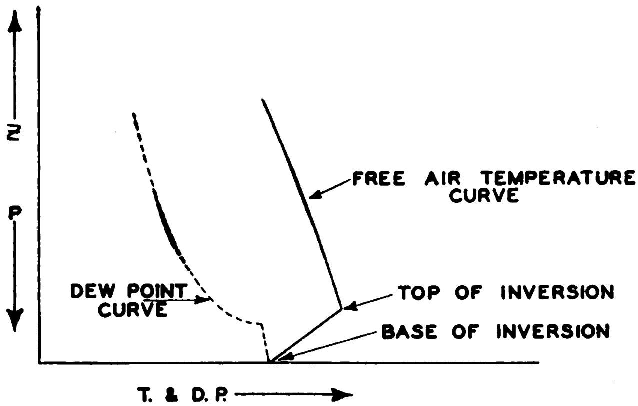


FIGURE 127.—Lapse rates of temperature and dew point in a ground fog.

chief heat absorbing agent in the atmosphere, dry air aloft is favorable to rapid cooling at the ground and the formation of ground fog. High water content in the upper air or a deck of clouds will usually prevent the formation of ground fog. A source of moisture such as a lake, the ocean, or wet ground will aid greatly in the formation of ground fog. The transpiration of plants also provides a prime source of water vapor. The winds near the center of a high pressure area are usually light, the upper air is dry and, if there is a moisture source present, ground fogs may be expected. Winds in excess of 15 miles per hour will dissipate a ground fog because they mix the colder air with the warmer and drier air above. In a ground fog, the base of the inversion must always be at the ground as shown in figure 127.

(*b*) *High inversion fog.*—This fog occurs only over land in winter. It is formed as a result of the stagnation of a moist air mass in a given area for a number of days. It starts out as a ground fog then continues to get thicker on successive days due to the net loss of heat by radiation. The subsiding air aloft intensifies the inversion and

further prevents air movement in the lower layers, thereby acting as a seal which allows the air underneath to become colder and colder in increasing thickness. The lapse rate within the fog may be isothermal or show a slight decrease of temperature with altitude up to the base of the high inversion which may be as high as 600 feet above the ground. This fog may be low stratus during the day and become dense fog at night. It may occupy an area for several days and sometimes for weeks. It occurs chiefly in the higher latitudes. Conditions essential to the formation of this fog occur in the valleys along the Pacific coast in winter. Polar Pacific air moves into these valleys and then stagnates under the influence of the Great Basin High. Fogs of this nature have been observed to extend from Grants Pass, Oreg., to Bakersfield, Calif., and to remain there for periods as long as 14 days.

(2) *Advection fog.*—This type of fog occurs due to the movement of warmer air over a colder surface. A warm air mass will be cooled

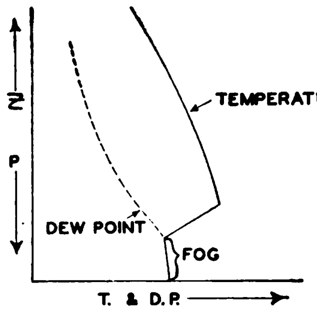


FIGURE 128.—Lapse rates of temperature and dew point in a high inversion fog.

from below by the surface over which it is traveling. This cooling creates thermal stability. The stability hinders turbulence and convection and confines the moisture to the lower levels. Fog and low stratus are typical warm air mass phenomena. A pilot flying in a warm air mass should be continually on the watch for the formation of fog or low stratus. The most critical time is at night because then the ground is coldest and becomes progressively colder from sundown to sunrise. When the ground is free from snow, the ceilings will usually become zero only at night to rise gradually after sunrise. Snow-covered areas maintain a low surface temperature that does not vary a great deal between day and night. Tropical air masses moving over a snow surface cause low to zero ceilings both during the day and night. Fog which forms at one place and then is carried by the wind to another is a type of advection fog. Low stratus that moves over higher ground causes fog at the higher elevations. This is the type of fog that is noted when the low clouds are seen to cover

the surrounding hills or higher ground. During the day, the higher ground is usually warmer than the air and will tend to maintain some ceiling but at night it will often be colder than the air tending to draw the ceiling down. The sea-level elevation of the ceiling at night will often be actually less over higher ground. Low stratus with a ceiling 400 feet above sea level will cause fog above the 400-foot contour. If the top of the stratus is at 800 feet, the 800-foot contour determines the other fog boundary.

(a) *Land and sea breeze fog.*—Contrasting surface temperatures exist at almost all seasons of the year along seacoasts. The ocean is an abundant moisture source. These factors combine to make coastal areas subject to frequent fogs. In winter, the land is usually colder than the ocean and fogs may be expected with an onshore wind. In summer, the ocean is usually colder than the land so fogs may be expected when the offshore breeze contains considerable moisture. The prevailing wind drift in the middle latitudes is from west to east. Therefore, over land, fogs may be expected along the Pacific coast with a normal pressure gradient. Cyclonic circulation is usually required to produce onshore fogs along the Atlantic coast. During both winter and summer, the offshore winds along the Pacific coast are unusually dry. Fogs in that area with an offshore breeze are rare. In fact, an offshore breeze usually means clear weather. Along the Atlantic coast in summer, the offshore winds usually consist of TG air which contains an abundant moisture supply for the formation of fogs. Along the southern Atlantic coast and in the Gulf of Mexico the sea surface temperatures are unusually high and usually prevent the formation of offshore fogs. Farther north, especially around New England, the Labrador Current causes low sea temperatures and offshore winds in this area may produce thick fogs. Along the Pacific coast from southern California to central Washington, there is a belt of water which is several degrees cooler than that farther at sea. The greatest contrast is in the vicinity of San Francisco as shown in figure 129. The sudden cooling of the moisture-laden prevailing westerlies as they pass over this belt of cold water rapidly reduces them to saturation and causes fog. An onshore breeze carries this fog inland. The prevailing wind along the Pacific coast is from the northwest. From the sea temperatures shown in figure 129, it is seen that northwest winds will continually strike colder water along the Pacific coast from central Washington to a short distance south of San Francisco. The continued cooling of the lower layers keeps the fog on the surface and maintains this fog as a true fog as it comes on shore. Farther south, the northwest winds are warmed slightly in

the lower layers by the gradually increasing temperature of the sea surface. This effect, combined with the mixing in the lower layers due to strong winds, causes the base of the inversion to rise as shown

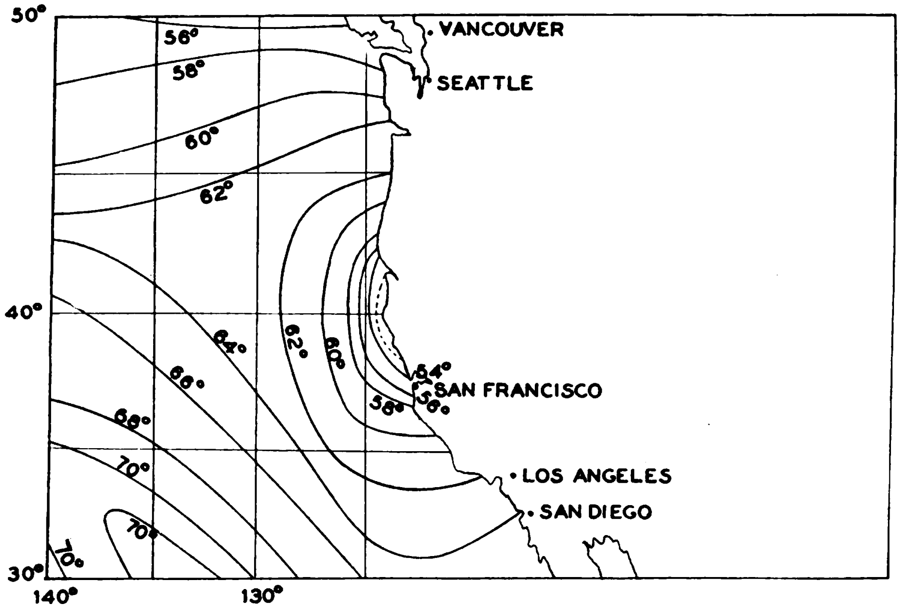


FIGURE 129.—Sea temperatures along the Pacific coast.

in figure 130. The lowest temperature in the free air is now some distance above the surface of the ground and, since that is where the cloud will form, it becomes low stratus instead of fog. It is this type of fog which has been termed "high fog" by western meteorologists.

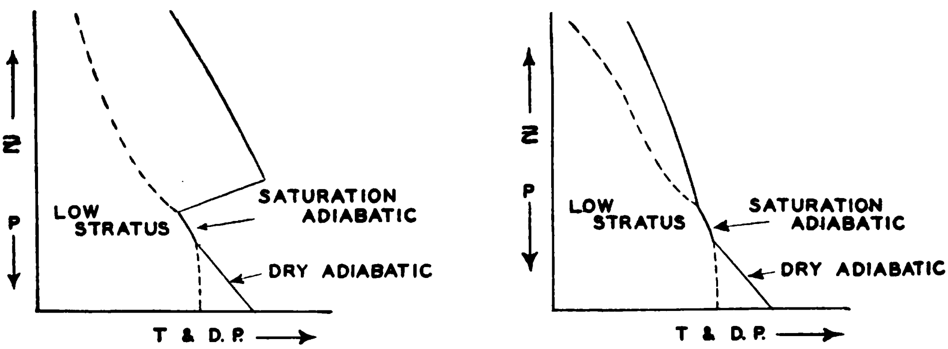


FIGURE 130.—Lapse rates of temperature and dew point in low stratus (high fog).

It becomes a true fog when it moves over higher ground elevations. Frequently at night, ground temperatures are reduced sufficiently to cause the low stratus to come down to the ground along the immediate seacoast. In summer, the sea breeze strengthens the onshore wind and the contrasting sea surface temperatures have their greatest differential. Coastal fogs along California and Oregon are to be

expected more often in summer. They are the chief hazard to aviation and the forecaster's main problem during this period. The sea breeze attains its maximum strength in the afternoon and that is the time when the fog begins to roll in from the ocean. It continues to come in until late at night and remains until sunrise. Then surface convections begin, the ceiling gradually lifts, the clouds dissipate, and the ceiling usually becomes unlimited later in the morning. The sea temperatures are in the fifties and land temperatures in this area in the summer may go above 100°. The sea breeze forces the warmer air aloft to create a very strong inversion. This inversion confines the sea breeze, prevents mixing, and holds the cold ocean air next to

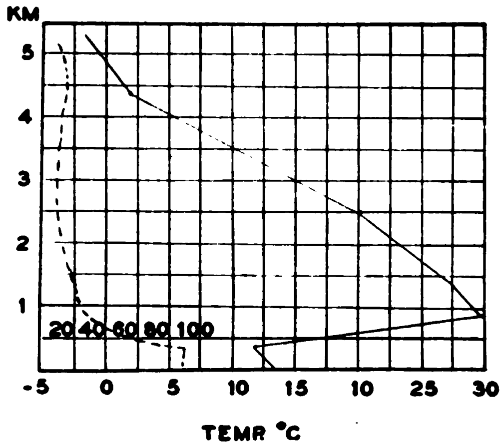


FIGURE 131.—Temperature-altitude curve at Oakland, Calif., on August 19, 1937.

the ground. A temperature of 85° F. at the surface in San Francisco is rare. Figure 131 shows a typical inversion along the Pacific coast in summer. The sea breeze averages about 22 miles per hour in the early afternoon at San Francisco in the summer.

(*b*) *Sea fog.*—This fog forms when sea air is cooled over cold ocean currents. The example given in (*a*) above along the Pacific coast fits this type. The most pronounced example occurs in the Atlantic Ocean when air that has been over the Gulf Stream moves over the Labrador Current. In January, the temperature differential across a belt about 140 miles wide between these currents off the southeast coast of New England is 22° F. as shown in figure 132. Thick, dense fogs occur north of the boundary between these currents when the wind has a southerly component. The frequent fogs of the Grand Banks are formed in this manner. When the wind is unusually strong, the fog will lift to form low stratus. This relation between wind velocity and ceiling should be true for any type of advection fog. Normally, the temperature gradients over the surface of the ocean are gradual.

The sea surface temperature gradually decreases from low to high latitudes. Air that moves over the ocean from tropical regions toward polar is continually being cooled. Extensive fogs frequently occur when tropical air masses move to polar areas. An example of this type of fog occurs on the western limb of the Pacific anticyclone. Tropical Pacific air is almost continuously carried northward over a successively colder ocean surface. Under the influence of this circu-

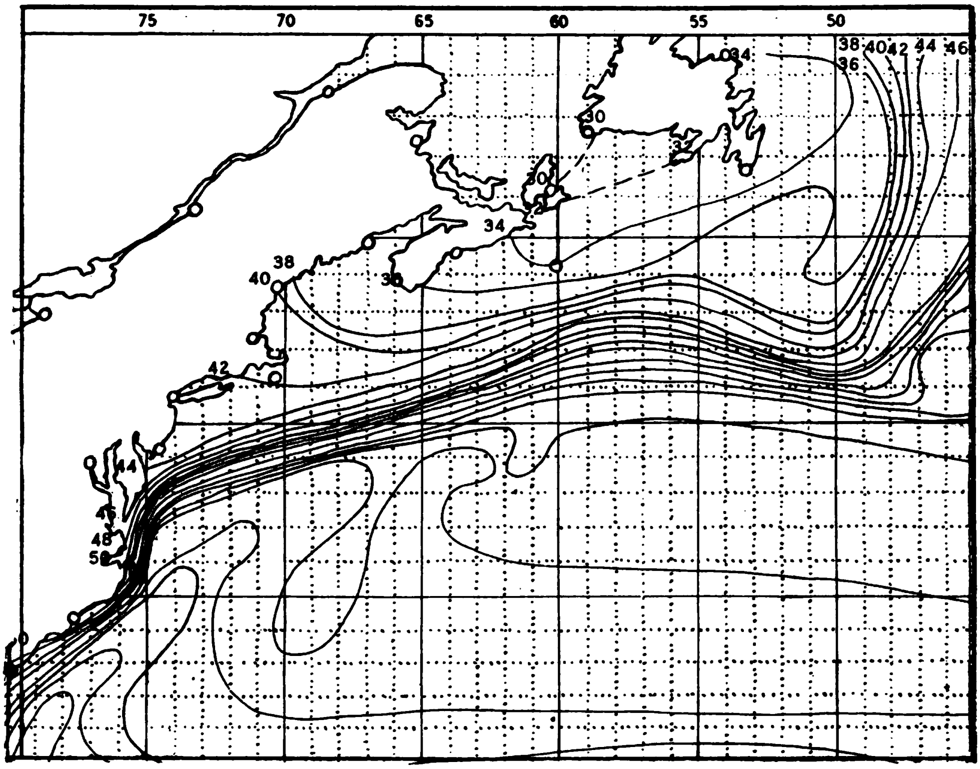


FIGURE 132.—Sea temperatures along the North Atlantic coast.

lation, very extensive fogs and low clouds exist over the north central Pacific Ocean during almost the entire year.

(*c*) *Steam fogs.*—Shallow, wispy fogs are formed when cold air moves over a much warmer surface. This type of fog occurs frequently in arctic areas when extremely cold air masses move over open stretches of water and is called "arctic smoke." The same phenomena occurs in the middle latitudes to a much less pronounced degree. Early morning mists and steaming over lakes or lagoons are other examples. This fog is never thick and offers no hazard to air navigation.

(3) *Up-slope fog.*—This is a particular type of advection fog that has derived its name from a continual flow of air up a long, gradual

slope. It occurs most frequently along the eastern flank of the Rocky Mountains when the winds have a southeasterly component. When flying westward over the Great Plains area, the ceiling may often be noted to gradually decrease until it comes down to the ground. Clouds that surround any mountain or hill cause fog in the cloud area. These are not generally known as up-slope fogs but are actually often formed in the same manner.

(4) *Double inversion fog and low stratus.*—This type of fog or low stratus occurs under conditions similar to those required for the formation of low stratus. Low stratus may or may not previously exist. It occurs after sunrise and has been called "day fog." During the night, after an adiabatic lapse rate has been established in the lower levels by the wind, the wind frequently dies down and allows the

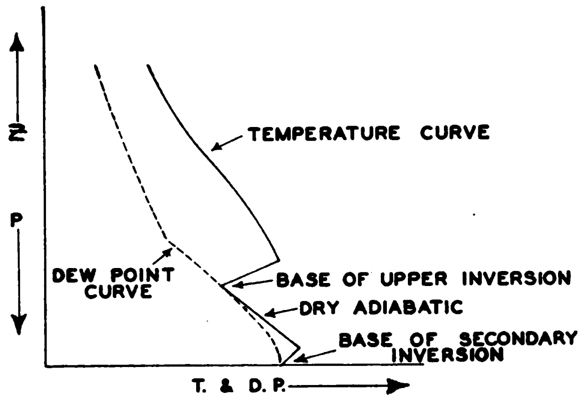


FIGURE 133.—Nocturnal double inversion.

development of a second inversion with its base at the ground as shown in figure 133. The lower inversion prevents convections from the ground and allows a higher concentration of moisture in the lowest levels. Transpiration of plants and evaporation from the ground supply the moisture. Soon after sunrise, the heating of the ground destroys the lower secondary inversion with the result that the condensation level of the lower layers is reached below the base of the upper inversion. A rapid lowering of the ceiling ensues. Ceilings that were previously about 1,000 feet may fall below 600 feet within a few minutes and may sometimes come close enough to the ground to form fog. The ceiling is usually indefinite and appears very ragged. To a ground observer, the ceiling may be 600 feet but to a pilot, the horizontal visibility at 300 feet may be zero. There may be frequent breaks giving the lower layers of air the appearance of being in an extreme state of flux. Extremely low ceilings are of short duration. Further rising of the sun with an increased rate of insolation causes the

ceilings to rise rapidly. The entire sequence of events may occur within an hour.

b. Frontal fogs and low stratus.—A front lies in a trough. The pressure in any given area decreases upon the approach of a front. A decrease in pressure brings the air nearer to saturation. The pressure distribution in a frontal zone aids in the formation of fog. The winds converge along a front and around cyclonic centers. Convergence requires lift and lift brings the air nearer to its saturation point. The precipitation in frontal zones increases the moisture content of the air near the ground. Fronts usually move over precipitation areas. The wet ground furnishes a moisture source. Cloud systems associated with fronts cut down the amount of insolation received at the ground and keep the lower layers of air cooler. Lower tempera-

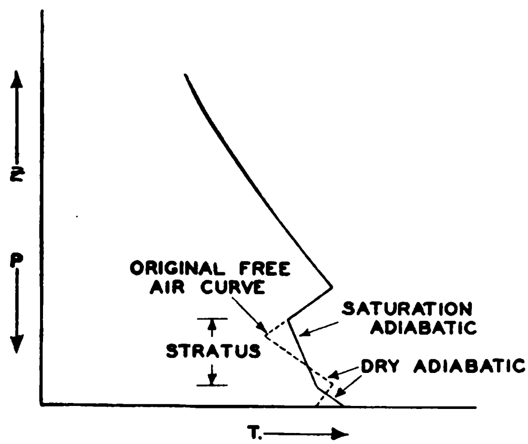


FIGURE 134.—Double inversion; low stratus or fog.

tures aid in the formation of fog. The warmer air masses are lifted in frontal zones. For air that is already near saturation, this lift is frequently sufficient to cause fog or low stratus.

(1) *Warm front fogs.*—Some of the most widespread and dangerous fogs occur ahead of a warm front. This is particularly true in winter when the front is between Tg and Pc air. There is a large temperature differential between these air masses and the resulting cyclonic systems are strong. Precipitation may extend over a wide area; the Pc air is already close to saturation and the added moisture is frequently sufficient to cause widespread fogs and low stratus. There is a rapid pressure fall ahead of these systems. This pressure decrease often occurs quite suddenly over large areas and it may be just enough to bring unsaturated air to the saturation point. The ceilings may rise during the day to 800 or 1,000 feet but with nightfall they rapidly come down to very low levels and often cause fog. The pilot who

finds himself near the center of one of these widespread areas where fog is rapidly forming is in dire straits. An adequate reserve supply of fuel may carry him out of danger but many airplanes do not carry such quantities of fuel, especially after a portion of the original capacity has been used. With the strong winds that accompany an intense cyclonic system, the cloud formations ahead of a warm front are usually low stratus. Even with the strong winds, the ceilings may be below the minimums required for safety. Contact flying in this type of weather is exceedingly dangerous.

(2) *Cold front fog.*—A cold front fog differs from that of a warm front fog chiefly in its much narrower extent. Widespread fog or low stratus may develop along and in rear of a cold front that is rapidly decelerating or becoming stationary. This occurs when the warm air is actively overrunning the cold air. The fog and low stratus are similar to those ahead of a warm front.

(3) *Front passage fog.*—Many factors included in the formation of fog in frontal zones have been previously mentioned. Fog may be expected in any frontal zone where the temperature and dew point are close together. When the winds are light, the mixing of the warm and cold air masses may produce a fog. The movement of the air in a frontal zone over much colder ground may cause the required cooling. Strong fronts often carry a heavy cloud system that reaches to the ground and sometimes appears like a dark wall. Cloud systems similar to this have existed along stationary fronts and closed in a given area for days at a time. Other times the cloud system may be very light and pass across a station in the form of a narrow band of fog or low stratus. All variations between these two extremes may be expected.

108. Time of formation.—*a.* Most fogs are formed by a combination of the processes of advection and radiation. Cooling of the air by radiation occurs chiefly at night and advection continues both during the day and night with the winds stronger during the day. Light winds favor the formation of fog. If fog is expected and the winds pick up, low stratus will probably occur. The fog hazard is much more serious at night than during the day. Many pilots who are not flying aircraft today, would be, had they realized the importance and use of the information that the air is cooler and nearer saturation at night and that fog is largely a nighttime phenomenon.

b. One way a pilot may keep himself informed as to the possibility of fog is to keep track of the rate of approach of temperature to dew point on successive weather reports. This may be done mentally but it is better done graphically as shown in figure 135.

c. Successive reports of the temperature and dew point over a period of 2 or 3 hours, or even longer, give the rate of approach of the temperature to the dew point. This rate of approach may be extrapolated forward to give the time when these two elements will become the same. Fog may be expected then. When the temperature-dew point curves are plotted (fig. 135), they may be extrapolated forward until they intersect. Their intersection gives the expected time of the formation of fog. There are many factors which may change the rate of approach of the temperature to the dew point, so this device of forecasting the time of formation of fog is not infallible,

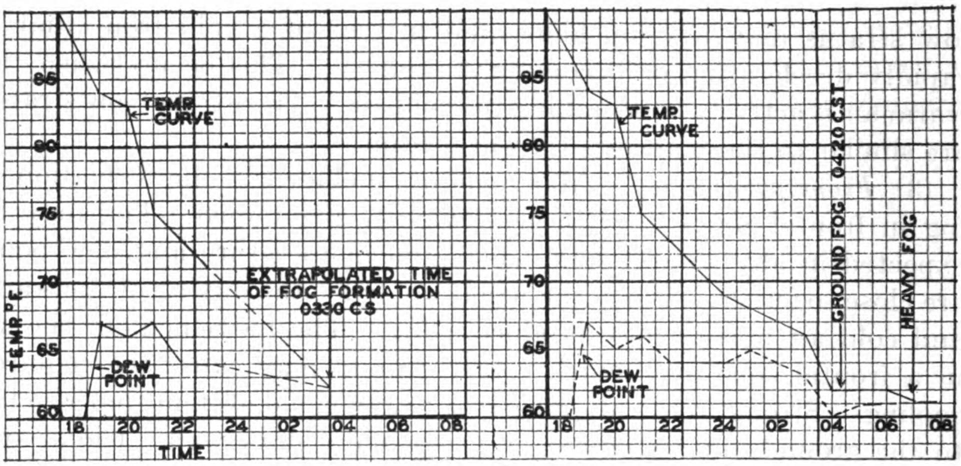


FIGURE 135.—Extrapolated and actual temperature-dew point curves.

as shown in figure 136. However, it does give an indication that fog is possible and awareness of this fact is valuable information.

d. The air becomes progressively colder during the night. The possibility of fog increases from sundown to sunrise, except for double inversion fogs which form shortly after sunrise. Frontal fogs may occur at any time and are more dense at night.

e. The time of formation of fogs may be most accurately determined by obtaining the free air temperature-altitude curve in the late afternoon and then determining the decrease in ground temperature that will occur under the existing conditions of wind, moisture distribution aloft, wetness of the ground, and cloud cover. If these criteria are determined accurately, extrapolated temperature-altitude curves for that night will show if and when the fog will form.

109. Time of dissipation.—Fog and low stratus tend to dissipate after sunrise. The thicker the fog or clouds, the longer it will take for them to dissipate. A rough rule states that the clouds will become thinner at the rate of 300 feet per hour for each hour after sunrise;

that is, fog 600 feet thick would require 2 hours to dissipate. This is only a rough rule and often does not work, for example, double inversion. In tropical air masses, the lapse rate above the clouds is usually steeper than isothermal and approaches the pseudo-adiabatic. Low stratus formed in these air masses becomes thicker as the day progresses, but it usually breaks into cumulus clouds which may cause showers and thunderstorms in the afternoon. The chief factors in the time of dissipation of fog or low stratus are the lapse rate above the clouds and the thickness of the cloud formation. With an early morning free air curve, there are means available to the forecaster

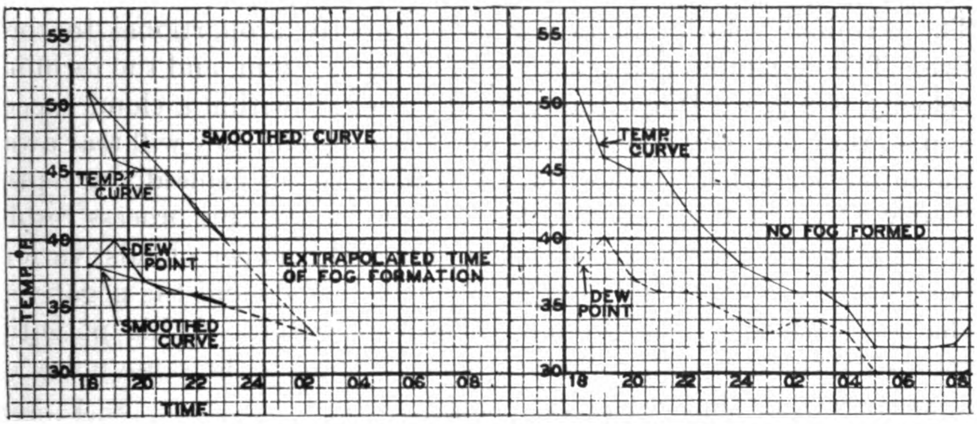


FIGURE 136.—Fog expected from extrapolated curves but did not occur.

that he may use to accurately determine the time of dissipation of fog or low stratus.

SECTION XIII

THUNDERSTORMS, TORNADOES, AND DUST STORMS

110. General.—A thunderstorm represents a very unstable condition in the atmosphere. To be reported as such, a thunderstorm must contain visible lightning or audible thunder or both. When clouds have the typical appearance of thunderstorm clouds but neither of the above phenomena is discernible, the clouds are reported as "thunderheads." Thunderstorms always constitute a hazard to avia-

tion. They should be avoided insofar as possible. They may be classified as—

a. Air mass thunderstorms.

b. Frontal thunderstorms.

111. Theory of thunderstorms.—*a*. Any current thunderstorm is one which develops as the result of the interactions within one or more air masses. It is a shower in which the degree of instability is high enough to cause vertical velocities of sufficient extent and magnitude to produce lightning and thunder. A raindrop consists of positively and negatively charged particles with the negative particles being more highly concentrated in the outer portions of the drop. The terminal velocity of raindrops is directly proportional to their size. The maximum diameter of a raindrop is 5 mm. and the terminal velocity is 8 m/s. When the upward velocities within a cloud exceed 8 m/s., they not only will support all raindrops but they will tear away the outer portions of each drop. According to the generally accepted theory which may be modified by current studies, this process results in the establishment of an electrical potential between clouds, various portions of a single cloud, and between the clouds and the negatively charged surface of the ground. The destruction of this potential causes lightning and the accompanying thunder is the same noise, on a large scale, as that caused by a spark gap.

b. The strongest lightning discharge may be conducted by a metal rod the size of a man's thumb so there appears to be little opportunity for serious structural damage to a metal airplane by lightning. However, trailing antennae offer a very convenient path for lightning and several cases have been reported where radio sets have been seriously damaged with some discomfort to the radio operator. Older airplanes of the "stick and wire" type present several points at which lightning may cause damage, one of the most notable of which is at control cable junctions, particularly at the ailerons. Present records show no airplane casualties due to lightning itself.

112. Mechanics of a thunderstorm.—*a*. The vertical velocities necessary in thunderstorms may be initiated in one or more of the following ways:

(1) Frontal activity.

(2) Establishment of super-adiabatic lapse rates by—

(*a*) Diurnal heating.

(*b*) Radiation.

(3) Topographic influences.

(4) Convergence.

b. The vertical motions are perpetuated and strengthened by air

that is unstable for the saturated state. Showers or thunderstorms result depending upon the degree of this instability. Essentially then, thunderstorms result from the lifting of the air to its saturation level by one of the above means from where it is aided in its upward

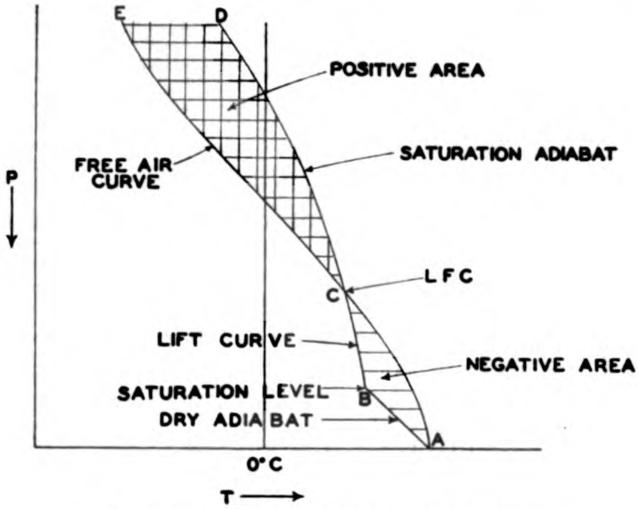


FIGURE 137.—Thunderstorm due to forced lift

movement by the instability of the saturated air, particularly after it has reached the level of free convection. The level of free convection, LFC, is the point above which the rising air is warmer than the

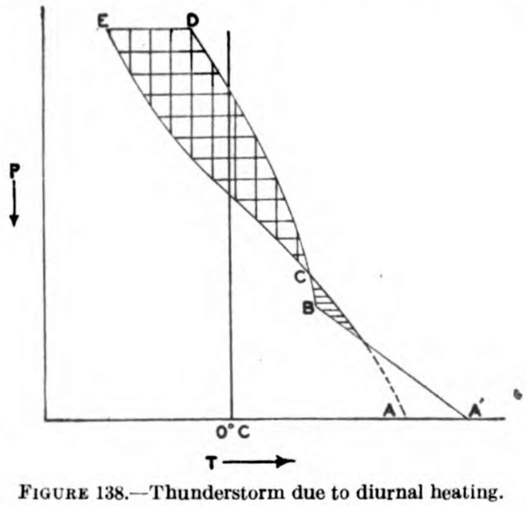


FIGURE 138.—Thunderstorm due to diurnal heating.

surrounding air and is represented by point C in figure 137. The air must be lifted to the LFC through the force of frontal activity, terrain effects, or convergence. Above the point B the lifted air is saturated and its temperature decrease with altitude is that of the saturation adiabatic BCD. Above C, the rising air is continually

warmer than the surrounding air and will be accelerated in its upward movement. The vertical motion will only be suppressed when the rising column reaches a stable layer of air, perhaps the base of the stratosphere. The negative area is that portion of the diagram where the rising air is colder than the surrounding air and the amount of resistance to vertical motion is measured by the size of this area. The positive area shows where the moving air is warmer than the surrounding air and the size of this area gives a measure of the energy available for thunderstorms activity. As yet, no method has been devised whereby the vertical velocities to be expected in a thunderstorm may be accurately determined from a thermo-dynamical diagram.

c. The almost complete destruction of the negative area has been accomplished in figure 138 by diurnal heating which has raised the temperature of the surface air from *A* to *A′*. This figure represents the usual relationships existing in an air-mass thunderstorm.

113. Air-mass thunderstorms.—*a. General.*—(1) An air-mass thunderstorm is one which develops as the result of the interactions within a single air mass. This is the simplest type of thunderstorm and is usually due to diurnal heating in the lower levels of the atmosphere with attendant super-adiabatic lapse rates near the ground. Isolated, irregularly spaced convections begin at the ground and reveal themselves to the pilot early in the day in form of "bumps." Later, these small convections are strengthened by merging and additional heating until they form a rapidly growing cumulus cloud which develops into a thunderstorm, usually in the afternoon. Thunderstorms that occur earlier in the day usually have some primary cause other than diurnal heating. The setting of the sun cuts off the primary source of energy for air-mass thunderstorms. They then tend to dissipate and disappear. Some of them attain such strength in the afternoon that they persist until late at night. Forecasting the time of dissipation of a thunderstorm is indeed difficult, being dependent on so many variables that are usually unknown to the forecaster.

(2) If the air is potentially unstable and diurnal heating causes convections to the saturation level, showers may be expected. A rough rule states that a decrease of equivalent potential temperature with altitude exceeding 6°C/km. throughout a layer at least 2 kilometers thick is required for the formation of thunderstorms. The time when the thunderstorm will begin is dependent upon the rate of diurnal heating and the degree of potential instability, but will usually be about 1 or 2 hours after the rising air has reached the level of free convection. Once the thunderstorm is started, it aids con-

vections ahead of it and depresses those to the sides and rear. Thus each storm becomes isolated. Over a large area air-mass thunderstorms are scattered. They should present no serious hazard to the pilot, since it is possible for him to avoid the individual storms.

(3) Air-mass thunderstorms vary considerably in area and in velocity. However, they usually travel at about 15 to 20 miles per hour and are 8 to 40 miles in width. The period of hazardous flying at any one station is of relatively short duration; an hour is exceptional.

b. Motions and appearance.—(1) Thunderstorms develop from cumulus clouds and cumulus clouds result from vertical currents, so vertical currents are expected in thunderstorms. Above the LFC, the rising air is accelerated. This means increasing vertical velocities until a stable layer is reached and for air-mass thunderstorms such a layer is not usually reached below 20,000 feet. Hence the strongest vertical currents may be expected in the upper portions of the clouds. The anvil-topped cumulus cloud is associated with thunderstorms because the anvil top indicates that the cloud extends to very high levels and the convective activity must have been strong to carry the cumulus cloud to that elevation. The anvil top is due to the spreading out of the top of the cloud at the base of a stable layer which the cloud cannot penetrate.

(2) The rising currents within the cloud are associated with compensating down currents both within and without the cloud. Vorticity results and visible curls are produced which give the cloud its cauliflower appearance, especially in the lower levels. When the cloud reaches a level where the water droplets freeze, the cloud assumes a fibrous appearance. The fact that the cauliflower appearance is often observed to considerable distances above the zero isotherm indicates that such clouds contain water in liquid form at temperatures well below freezing.

(3) Vertical velocities are frequently sufficient to cause a rate of rise of 3,000 feet per minute to be indicated on the climb indicator. Pilots have reported several thousand feet of rise in a thunderstorm with the airplane in a dive. Vertical velocities exceeding 200 miles per hour probably exists in severe storms. The strong up currents alone are not hazardous but when they are associated with adjacent down drafts, exceedingly high velocity gradients are created. Load factors far in excess of the safety factor built into airplanes may be encountered, and if so, structural damage will certainly result. Spars have been cracked, ribs broken, fuselages twisted, and safety belts torn loose in thunderstorms.

(4) Violent turbulence renders some flight instruments useless, particularly the turn and flight indicators. The bank and turn indicator may quickly indicate its maximum values with the pilot having no true knowledge of the rate of turn or degree of slip or skid. Manual control of the airplane has been reported as impossible due to the tremendous forces on the control surfaces.

(5) A thunderstorm moves in the direction of the prevailing wind. It is fed chiefly by the rising air at the front edge of the cloud as shown in figure 139. It is in this portion of the cloud that the rising currents attain their maximum velocities and there the lightning is most frequent. The direction of motion of a thunderstorm at night may

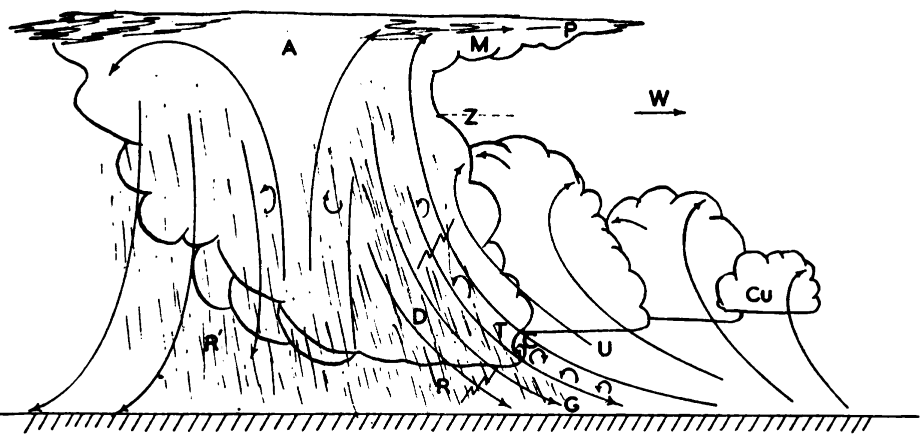


FIGURE 139.—Vertical section of an air mass thunderstorm. *A*, anvil; *C*, roll cloud; *Cu*, cumulus clouds; *D'*, descending air; *G*, strong gusts; *M*, mammato cumulus; *P*, protruding portion of anvil; *R*, primary rain; *R'*, secondary rain; *T*, severe turbulence; *U*, up draft; *W*, wind; *Z*, zero isotherm.

be determined from some distance by noting the position and movement of the lightning. Usually the wind velocities at the higher levels in a severe thunderstorm have greater values and are in approximately the same direction as at the base of the cloud. The anvil or fibrous portion of the cloud stretches out in the direction of motion of the storm and may be observed from relatively great distances depending upon the altitude of the airplane.

(6) In clear air, the distance in miles from which objects may be seen from the ground $=\sqrt{3/2h}$, when h is height in feet. A thunderhead extending up to 30,000 feet may be seen from a distance of more than 200 miles when the observer is on the ground and the air is clear. When haze obstructs visibility in the lower levels, a pilot at 10,000 feet can usually see thunderheads 225 miles away without difficulty.

(7) The descending rain drags air with it causing downward currents as shown at D in figure 139.

The evaporation of the rain cools the sinking air. The descending

cold air moves down and forward in a fan shape. In an arid region, this may kick up a ring of dust ahead of the thunderstorm. The cooler down currents may attain velocities of 60 to 70 miles per hour in strong gusts as they move along the surface just ahead of the storm.

(8) The region of most severe turbulence is between the descending and rising air in the forward portion marked *T* in figure 139. A roll cloud *C* is sometimes formed at the lower forward edge of the main cloud. Airplanes in this region have been violently rolled beyond control of the pilot. Severe turbulence also occurs in the rapidly forming clouds just ahead of the main cloud. The formation of these clouds explains the often noted movement of a thunderstorm at a greater velocity than exists in the prevailing wind. A thunderstorm persists due to the rapid cloud growth in its forward portion. The forward moving cold air ahead of the storm forces the warm air aloft. A series of actually new thunderstorms are continually forming in advance of the older ones, often giving the impression of an excessively rapid movement of the original storm.

(9) On a hot summer afternoon, when the base of scattered cumulus clouds may be at 5,000 or 6,000 feet, the ceiling in a thunderstorm may drop to about 500 feet and the visibility may be reduced to a few hundred yards in the heavy rain. Usually, however, the ceiling is about 1,000 feet and the visibility in excess of 1 mile. Therefore, a flight through a thunderstorm would often be in violation of Federal regulations unless an instrument flight were authorized and instrument flight in a severe thunderstorm may be impossible. Flight over the top is impossible without oxygen equipment. Even then it is impossible with most existing equipment due to lack of sufficient service ceiling.

(10) The descending currents in the rear portion of the cloud and the mixing with the surrounding drier air act to increase the saturation level and dissipate the cloud. The ceiling may rapidly rise from a few hundred feet in the forward portion to several thousand feet in the ragged clouds that are continually disappearing at the rear of the storm.

c. Dissipation.—Severe though some air-mass thunderstorms are, their persistence often hangs in a very delicate balance. If not a severe storm, it may stop quite suddenly, long before the sun goes down. Several factors may contribute to an early demise of a thunderstorm. Lack of these will aid in the persistence of the storm. Probably the most important effect is a reduction in the amount of insolation due to the interference of shower or thunderstorm clouds themselves, particularly if the upper air is close to saturation. The

expansion of the lower levels by diurnal heating combined with the lift in shower or thunderstorm clouds may cause the sky to become overcast and eliminate strong surface convections. This often occurs in very unstable air and prevents even the formation of thunderstorms, whereas otherwise they would have been expected. A shower in advance of a thunderstorm may stabilize the air and cool the ground sufficiently to stop the storm. A neighboring shower or thunderstorm cloud may cast a shadow in the path of a thunderstorm and thereby limit convections, especially about 3 or 4 o'clock in the afternoon. The rapid movement of a thunderstorm may carry it out of an area of convergence or into an adjoining portion of the air mass which is not sufficiently unstable to support the storm. A very stable layer aloft may cause intense lateral mixing or spread of the upper portions of the cloud. Reverse winds aloft often limit the shower cloud or drag away the upper portion of a thunderstorm which will limit the storm even though the upper air is sufficiently unstable. A change in the synoptic situation may cause changes in wind direction or subsidence where formerly convergence existed. There are various other factors which may effect a change in the delicate balance that determines whether thunderstorms will form or die out.

d. Sequence of events at one station.—During the approach and passage of an air-mass thunderstorm at one station the following sequence of events usually occurs, the more severe the thunderstorm the more pronounced each event:

(1) Light winds of warm air moving toward the approaching thunderstorm. The air feels uncomfortable, is sultry, and often almost calm. The barometer is unsteady down due to the decrease in pressure of the more rapidly rising air. The thunderstorm is visibly approaching and has an almost black appearance. Lightning may be visible, even during the day.

(2) The wind changes about 180° to away from the thunderstorm, picks up suddenly in velocity, becomes gusty, and is usually 10° to 15° cooler. If the soil is broken and dry and not protected by vegetation, dust will be kicked up. Parked airplanes that are not securely anchored may be tossed about. There is strong turbulence visible in the clouds overhead. Thunder is now audible since thunder cannot be heard at distances greater than 20 miles.

(3) Rain starts several minutes after the wind shift and pick-up. Usually a few large drops fall at first and then heavy rain occurs. Lightning bolts strike the ground. Thunder crackles. The ceiling comes down rapidly and visibility decreases. This usually lasts several minutes. Then there is a let-up, after which a secondary

heavy rain comes when the vertical currents decrease to the extent that previously held water is allowed to fall. The rain then decreases in intensity and the wind becomes almost calm. The thunder and lightning have moved on.

(4) The rain stops and the wind picks up a little from the direction of the thunderstorm that has just gone by. Ceiling increases rapidly and usually soon becomes unlimited. Visibility improves rapidly.

(5) Light wind shift of about 180° to the prevailing wind direction.

e. Terrain influence.—(1) Convections in air-mass thunderstorms must start at the surface except in a few cases where superadiabatic lapse rates are established at high levels. The lower layers must be very unstable if the terrain is smooth, whereas over mountains convections are rapidly set up and thunderstorms are precipitated more easily. The air around a mountain not covered by snow is heated faster than the surrounding air, thereby setting up convections. Tropical islands, especially those with mountains, cause thunderstorms due to convections set up on a hot day. The resulting showers may be very intense due to the large amount of water in the air. The amount of moisture that must fall out for a given amount of cooling is large. Thunderstorms usually occur on the lee side of mountains. On the windward side the down draft from a thunderstorm would oppose the up currents and nullify convections. On the lee side the thunderstorm downflow of wind aids air motion down the mountain side and forces air up ahead of it to aid the continuance of the thunderstorm. A thunderstorm goes down a canyon or steep valley if the upper air currents are very weak. The earth's deflective force sometimes deflects thunderstorms to the right.

(2) The sea breeze on the west coast meeting thunderstorms approaching from the east causes convergence and aids in maintaining thunderstorms in this region, particularly in southern California. Few air-mass thunderstorms occur along the north Pacific coast because of the stability of summer Pp and the rare appearance of Tg. Thunderstorms benefit by convergence with the sea breeze along the Atlantic coast. The general drift of thunderstorms is west to east, and the sea breeze on the Atlantic coast is east to west. The front edge of the sea breeze, the "sea breeze front," aids materially in the formation of cumulus clouds which sometimes develop into thunderstorms. This explains the more frequent occurrence of showers and thunderstorms several miles inland than along the seashore as the sea breeze attains its maximum value during the hottest portion of the day.

f. In tropical gulf air.—(1) Tropical Gulf air (Tg) is the only North American air mass which is normally sufficiently unstable for

the saturated state to produce thunderstorms. The warmth and moisture of the source region together with its proximity to the middle latitudes account, in part at least, for the resultant air mass that is unusually moist in the lower levels with a sufficient decrease of water content and temperature with altitude to make this air mass potentially unstable. A least 90 percent of all thunderstorms that occur in the United States occur in TG air. Their maximum frequency occurs near the Gulf of Mexico in the afternoon. Over the Gulf of Mexico, their maximum frequency is at night.

(2) The normal trajectory of TG in summer is onshore from the Gulf of Mexico. When TG air rises over the increased land elevations,

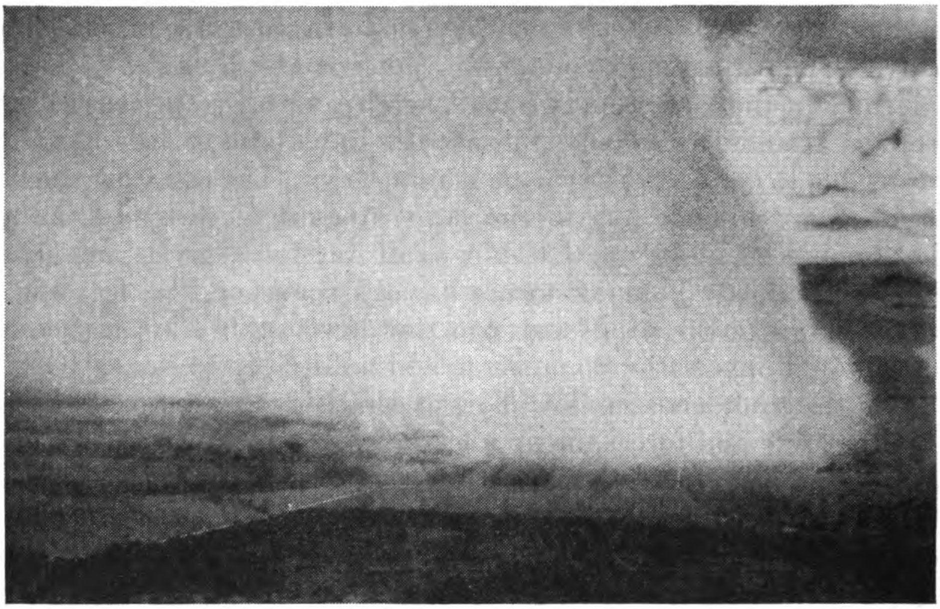


FIGURE 140.—Approaching isolated thunderstorm. Photograph taken near Austin, Tex., looking SE. from 2,000 feet, July 9, 1938.

especially in west Texas, the lift required for saturation gradually decreases except for a short distance onshore. By the time the air has reached ground elevations of 2,000 or 3,000 feet, the formation of thunderstorms is easy and a little added lift will cause them. This small added lift may be due to further progress up the gentle slope, slight convections from the mountains or superadiabatic lapse rates established by diurnal heating. Therefore the mountains in west Texas, New Mexico, Colorado, Arizona, California, Utah, and sometimes even Oregon, Washington, Colorado, Arizona, Idaho, Montana, and Wyoming, and the Ozark and Appalachian Mountains cause many thunderstorms. Ordinarily a front is required to produce a large number of thunderstorms over flat country. In summer, the

thunderstorm center of the United States shifts from Tampa, Fla., where it is located in the winter, to Santa Fe, N. Mex.

(3) A high level anticyclone consisting of dry warm air, now known as "Superior air," is semipermanent over the southwestern United States in summer. Its position may change irregularly to almost any portion of the United States. Wherever it happens to be located, thunderstorm activity is greatly limited if not nonexistent near the center. The TG air flows northward in thick streams around the peripheries of this anticyclone or portions of it when it breaks down. It is in these thick currents of TG that thunderstorm activity is to be expected. One such stream usually flows up over Mexico, Texas, and New Mexico and into the United States roughly between El Paso, Tex., and San Diego, Calif. Another such stream usually flows up between east Texas and Florida. It is the movement of either of these streams or a combination of the two, to the Mississippi Valley that brings thunderstorm activity to that region.

114. Frontal thunderstorms.—*a. General.*—(1) Frontal thunderstorms are those which occur as a result of vertical motions created by a front. The thermodynamical characteristics of a frontal thunderstorm are similar to those of an air-mass thunderstorm. The chief difference between them is that the frontal activity has lifted the potentially unstable air to its level of free convection. Very often the frontal activity is in conjunction with the other factors that cause lift. In a discussion of frontal thunderstorms, the factors affecting air-mass thunderstorms must be kept in mind. Frontal thunderstorms may not be diminished greatly by nightfall and they may originate and persist during the night. The origin and occurrence of thunderstorms at night are excellent clues for the pilot that he is in a region of frontal activity. Another important source of information is the distribution of thunderstorms. When they occur in a more or less continuous line or in close proximity, the pilot may be reasonably sure that they exist in or near a frontal zone.

(2) Hail occurs in connection with frontal thunderstorms. Hailstones remain aloft only as long as vertical currents are sufficient to support them. Their concentric growth, giving them an onion-like appearance in a cross section, shows conclusively that they have been subjected to successive periods of freezing. This implies that their vertical motions have been oscillatory between freezing and nonfreezing levels due to the changes in strength of the vertical currents which have been supporting them. Hailstones vary slightly in density and the velocities required to support them depend upon this factor as well as their general shape and roughness. Vertical veloci-

ties of approximately 100 miles per hour are usually required to support hailstones 2 inches in diameter. The shape of hailstones varies from approximately round to disk or platter-shaped. Round hailstones 5 inches in diameter have been reported. Such missiles present a hazard to aviation, especially where glass and fabric are encountered.

(3) Layers of air containing supercooled water may be quite thick, and hail forming in such layers may grow appreciably in size simply by accretion of the subcooled drops during one continuous fall of a hailstone. However, such accretion cannot account for the smooth concentric growth observed in large hailstones but may account for their often lumpy surfaces.

b. Warm front.—Warm-front thunderstorms are scattered in the area ahead of the warm front as shown in figure 141.

(1) When warm-front thunderstorms occur in the United States, the air in the warm sector is usually TG. Convergence in the warm

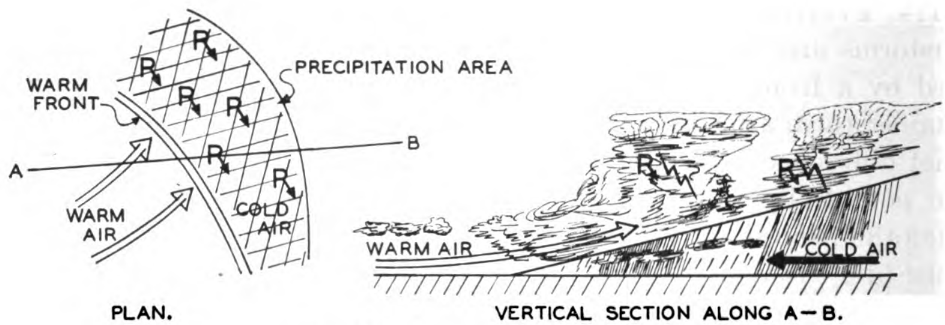


FIGURE 141.—Warm-front thunderstorms.

sector due to cyclonic activity may cause heavy showers and thunderstorms to occur in that region. The ceiling and visibility may become zero in the heavy rain.

(2) The time of formation and location of warm-front thunderstorms may be estimated from the slope of a warm front, the rate of flow over that front and the lift required for saturation. The heavy precipitation in thunderstorms ahead of the surface front makes the warm-front rains spotty. If air mass thunderstorms are probable, frontal thunderstorms are almost certain. The thunderstorms form in the altostratus clouds over the cold air. If the pilot can get above the altostratus clouds he is usually able to avoid the individual scattered thunderstorms. The precipitation from the thunderstorms combines with the warm-front rain to raise the relative humidity in the cold air, thereby decreasing the ceilings and enhancing the possibilities for fog. The direction of motion of individual thunderstorms may be determined from the winds aloft.

(3) In the Northern Hemisphere, the flow of air over a warm front is generally in a northeasterly direction, and warm-front thunderstorms usually move in that direction.

c. Cold front.—Because of the unusual steepness of the cold front, generally along the line of the surface front, the maximum lift in the warm air is produced suddenly along this front. The distribution of cold-front thunderstorms is usually limited to a zone about 50 miles wide along the cold front as shown in figure 142.

(1) Thunderstorms occurring in this zone are usually the most severe type encountered. They occur independently of the time of day. Along strong cold fronts they may form a continuous line of thunderstorms and this line is known as the "squall line." Expert instrument pilots who have flown into a squall line have been forced

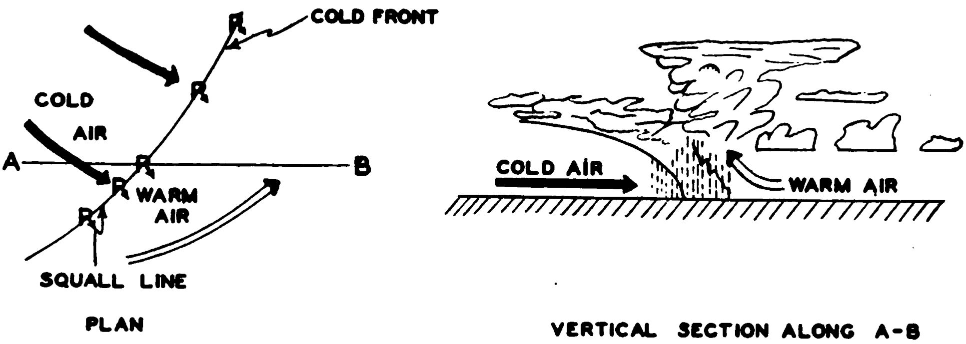


FIGURE 142.—Cold-front thunderstorms.

to turn back because they could not control their airplanes. One pilot related his experiences very briefly, "I went in at 12,000 feet and it spit me out at 18,000." A large percentage of all aircraft accidents due to weather occur along a strong cold front.

(2) Particularly in the south central portion of the United States, surface cold fronts carry thunderstorms and are frequently preceded by an upper cold front that is also causing severe thunderstorms. These upper fronts leave the surface in the western Great Plains district to move ahead of the surface front until they reach the Appalachian area. There they usually dissipate or rejoin the surface front. Figure 143 shows a plan and vertical section of an upper cold front between Tg and Pp air. When the warm air is in a transitional stage between Pp or Pc and Tg, it may not be sufficiently unstable to cause thunderstorms. If not, the rain produced may still be heavy. As shown in figure 147 the rain area may be of considerable width. This causes a large area of low ceilings and visibilities which for all practical purposes may be zero, particularly at night. This is also the area where pressures are changing rapidly. The altimeter must be

frequently reset to its proper value. The combination of circumstances outlined above has led to serious and costly airplane accidents.

(3) The thunderstorms occur in the warm air and the warm air usually moves to the northeast, hence the thunderstorms usually move to the northeast. The cold front usually moves to the southeast developing thunderstorms as it moves, thereby making it appear that the thunderstorms are moving to the southeast. When it is absolutely necessary to fly through a squall line, it is perhaps better to fly in the thickest part of the thunderstorm rather than the small clear spaces that may exist between thunderstorms, because there is usually more severe turbulence in or along the edges of a clear space. If the clear space is a mile or more in width, the vertical velocity

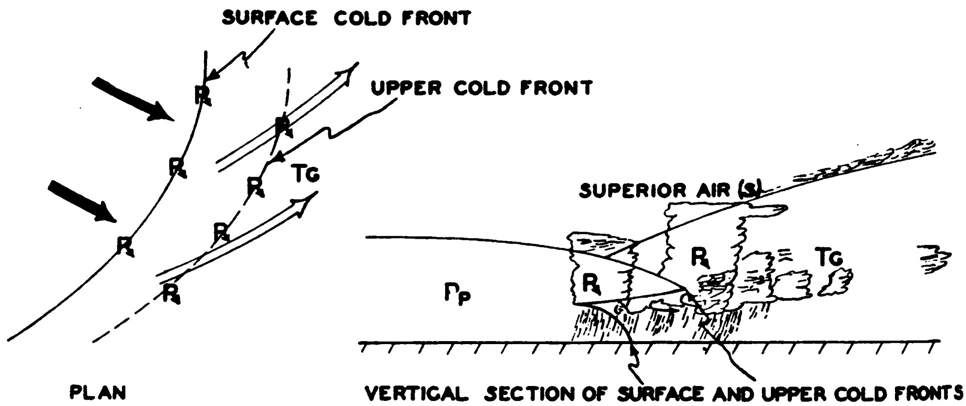


FIGURE 143.—Thunderstorms along surface and upper cold fronts.

gradients near the center will probably not be severe enough to prevent safe transit.

(4) It is desirable to fly along a cold front as briefly as possible. When the point of take-off and the destination require flight along the line of a cold front, it is better to alter the course so that the flight line is perpendicular to the front at the point of crossing as shown in figure 144.

115. Tornadoes.—A tornado is a very violent storm of small extent with intense cyclonic rotation accompanied by heavy rain, usually lightning, and frequent hail. Tornadoes are distinguished from hurricanes by their extent and continuance. They are usually only a few hundred yards in diameter and their track on the ground less than 25 miles in length. In the United States, they occur most frequently in the central portion of the Middle West but they have been reported from every State in the Union. Because of their short extent, they do not appear on a weather map and forecasting them is so difficult that most forecasters refrain from the practice.

a. Causes.—Tornadoes result from extreme instability and are almost invariably associated with severe thunderstorms. Most of the tornadoes in the United States occur in the late spring and early summer, with a secondary maximum in the fall. They usually occur along or a short distance in advance of a cold surface front between Pp and Tg air. Usually this surface front has, sometime in its trajectory east of the Rocky Mountains, acted like a warm front with the Pp air overrunning the Tg, and formed an upper cold front. Due to adiabatic heating, radiation, and surface heating, Pp air, during certain seasons in the western Great Plains district, becomes warmer than the Tg and overruns it. The ascent over the Tg air causes adiabatic cooling which may destroy this delicate stability relation between these two air masses. The wind velocities in the Pp and the discontinuity surfaces between the two air masses help to maintain the Pp above the Tg in their unstable relationship. Convective activity initiated in the Tg along the upper front helps to destroy this unusual situation of a more dense air mass overlying a lighter one and the resultant overturning probably aids greatly in the formation of tornadoes in this region. Each tornado is probably initiated by thunderstorm activity in Tg, and in most cases the thunderstorm activity is caused by the Pp lower or upper cold front. Tornadoes have been observed to occur entirely within one air mass but always in connection with thunderstorm activity. They apparently grow out of the roll cloud as it bends down toward the earth. This probably accounts for the close relation between tornadoes and thunderstorms.

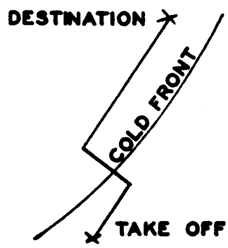


FIGURE 144.—Recommended flight path along a front.

b. Movements.—(1) Tornadoes build down from above.

(2) They may strike the surface at one point and then skip some distance before they reach the surface again.

(3) They move with the prevailing wind. The movement of the front may create new tornadoes giving a false impression of individual motion. Whether a tornado builds down to the surface or whether it apparently skips along depends largely upon the relation between the winds aloft and the surface winds. Strong winds aloft with light surface winds will cause the upper portion of the tornado to be carried ahead and may lift the tornado from the ground or destroy it completely. Winds aloft of about the same velocity as those near the ground will cause tornadoes of longest duration and intensity. The same factors which help or hinder convections in thunderstorms similarly affect tornadoes.

(4) Winds in a tornado vortex may exceed 500 miles per hour and the centrifugal force in a tornado causes a large reduction of pressure in the center of the whirl. Houses in the path of a tornado may seem to explode. Dust and debris are picked up by the suction effect giving the tornado the appearance of a black, sinuous cone extending from the ground up to the base of the clouds. The appearance is so typical and the extent so small that in daytime the path may be avoided without difficulty. Since, like thunderstorms, they move with the prevailing winds, the path of an observed tornado may be roughly forecasted. A pilot should never get caught in a tornado

FIGURE 145.—Small tornado in TG air at Randolph Field, Tex., September 15, 1938. It reached the ground later.

except possibly at night and even then the accompanying lightning should give a good clue as to its location.

c. Water spouts.—True water spouts are tornadoes that occur over water. They have been so named because of the ocean spray they draw into their funnels.

d. Whirlwinds.—Small whirlwinds frequently occur over land and are initiated by surface convection on hot days. When they pass over loose dry soil they form "dust devils" or "dust whirls." They may occur with clear skies. When they occur over the ocean they may be called water spouts.

116. Dust storms.—Dust storms are composed of dust picked up from the ground or a combination of dust and ashes from a volcano.

Volcanic dust storms rarely constitute a hazard to aviation, especially in the United States. Probably the most severe volcanic dust storm of recent years occurred when Krakatoa, a volcano in the East Indies, blew up in 1883. Dust and volcanic ash from this explosion circled the world several times and would have undoubtedly constituted a hazard to aviation near its source, had there been aviation at that time. Europe once experienced a black pall over the skies for almost an entire summer due to the eruption of a volcano in Iceland.

a. Sources.—The formation of a dust storm requires a dry source of loose soil or sand. Areas covered by vegetation or windbreaks con-

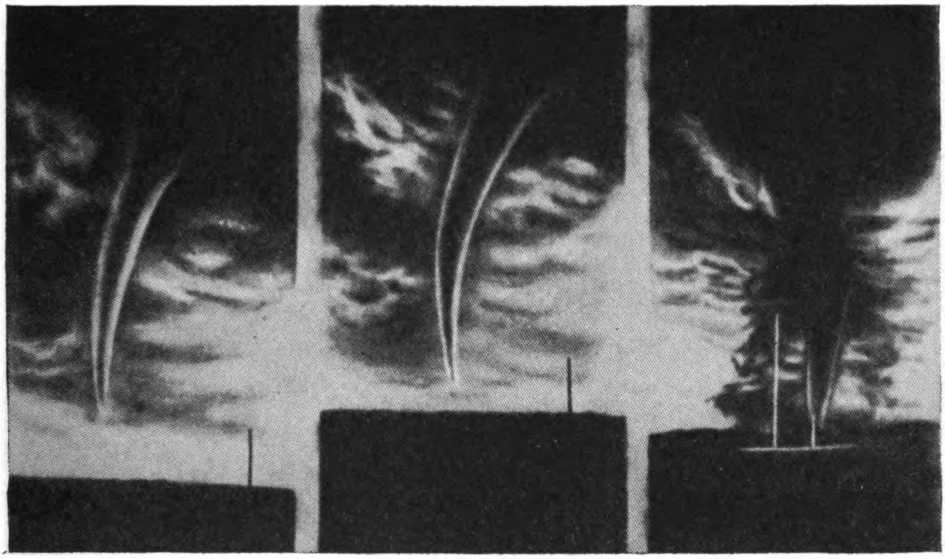


FIGURE 146.—Tornado forming and its progress. Left, tornado cone forming. Center, fully developed cone as it reached the earth. Right, tornado striking farmhouse which appears to explode.

sisting of rows of trees, even in arid regions, rarely provide a source for dust. Soil in arid regions, outside of sand-dune areas, that has never been cultivated is very resistant to erosion by winds. In these areas, dry stream and lake beds, freshly ploughed ground, dunes, and relatively bare ground are excellent dust sources. The condition of the soil and the expected wind velocities and direction are the factors for the forecaster to determine. Snow cover and recent rain will prevent the formation of dust. In arid regions, where run-off and evaporation are rapid, the effect of a recent rain may be shortly nullified. The forecaster must estimate when the ground will be dry enough for dust to be picked up. Wind velocities greater than 15 miles per hour will pick up dust but velocities of 25 miles per hour or more are required to pick up enough dust to cause a dust storm. These storms may be local in character or may cover several States.

Dust from the western Great Plains region has been observed in New England. The most severe dust storms in the United States originate in the "dust bowl" which includes the northwestern part of Texas, western Oklahoma, Kansas, Nebraska, eastern Colorado, and northeastern New Mexico. Dust storms from this region usually migrate to the south, southeast, and east behind strong cold fronts. Their eastern and southern limits are usually the Mississippi River and the Gulf of Mexico.

b. Characteristics.—A severe dust storm approaches the station as a long dense black cloud and may reduce the ceiling and visibility to zero. The front of the dust cloud may be hundreds of miles long

FIGURE 147.—Dry lake source of dust. Photograph taken 15 miles west of Guadalupe Pass, Tex., looking north-northwest from 9,000 feet on March 1, 1939.

and usually extends up to 10,000 feet and often much higher. The vertical extent of the dust storm depends upon the stability of the air mass in which it is formed. It may be limited by a strong inversion, but the velocities associated with dust storms are usually sufficient to cause the vertical extent to be as indicated. Dust picked up at the surface has been observed to reach the 15,000-foot level in 1½ hours. The frontal dust storm is usually so well defined that a pilot may alter his course to fit the situation. In the case of severe dust storms, the pilot must stay ahead of the front or land before the front passes because the ceilings and visibilities thereafter will be below the minimums required. Very low ceilings and visibilities may persist for several days or pass in a few hours, depending upon the situation and the location

of the station in reference to the dust's source. The farther away from the source, the more rapidly will the ceiling and visibility rise above the minimum requirements. The front of the dust storm moves with the velocity of the surface front. When reports are available, its rate of approach and time of passing at any particular station may be accurately forecast. Reports from pilots in the vicinity of a dust storm are of great aid to forecasters.

c. *Air masses.*—The dust storms behind cold fronts may occur in PP or PC air but usually they occur in PP because of its more unstable lapse rate even though frequently the velocities in the PC air are higher. The PP air may have recently come across the Rockies or

FIGURE 148.—Sandy soil, dry stream bed, and sand dune sources of dust. Photograph taken 20 miles east of El Paso, Tex., looking north from 8,500 feet on March 1, 1939.

may have had some period of stagnation in the southwestern United States. Dust storms do occur in the warm sector, particularly when it consists of modified PP air. These storms usually take a northeasterly trajectory and are frequently pinched out of TG with its showers, thunderstorms, and trajectory over a dust-free area.

d. *Local dust storms.*—These occur when either the source of dust is limited or the strong winds are local in character. Local sources of dust are usually dry stream and lake beds, sand dunes, unsurfaced and unsodded landing fields, and scattered areas of recently cultivated dry soil in arid or semiarid regions. Local strong winds result from topography, thunderstorms, tornadoes, or dust whirls. The "Santa Ana" of the Los Angeles Basin is a local strong wind resulting

from the orientation of adjacent mountains and passes to passing pressure systems. It comes from the northeast through Cajon and San Gorgonio passes, picking up dust and sand in the valley. It progresses southwestward in a well-defined stream, often beyond Santa Catalina Island. It has produced wind velocities in San Pedro Harbor that were destructive to shipping.

e. Blowing sand.—This occurs in sandy areas under the influence of strong winds. It remains at low elevations but has sufficient force

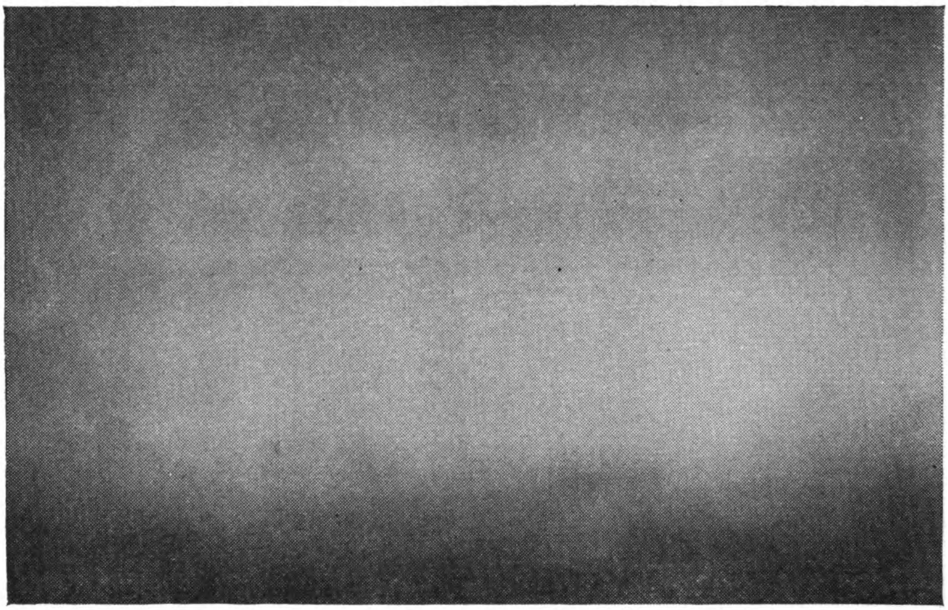


FIGURE 149.—Dust storm with rapidly lowering visibilities.

to scour paint and windshields and may cause damage to airplane engines.

f. Blowing snow.—This occurs when strong winds pick up fresh, dry snow. Visibility may be reduced to zero near the surface in blowing snow.

117. Hurricanes.—A hurricane is an unusually violent cyclone of tropical origin. In the East Indies and Chinese seas, a hurricane is known as a "typhoon." These storms are very destructive to shipping, cause heavy rains, excessive tides at adjacent coastal areas, and will dislodge works of man or nature that are not firmly anchored. They occur chiefly in August, September, and October.

a. Origin.—The origin of hurricanes has not been definitely established. One theory holds that they start from waves induced upon the equatorial front by the approach of a branch of the polar front. It is almost uniformly agreed that a hurricane starts when equatorial,

tropical, and modified polar air masses meet at a common point. This idea has been verified to some extent by the fact that many hurricanes have been found to occur along old polar fronts that have been carried into tropical latitudes. Assuming an established wave, the energy released by the heavy precipitation is so great that the young cyclone rapidly progresses until almost complete occlusion has taken place. Circular isobars about the center follow as with extra-tropical cyclones.

b. Characteristics.—The hurricane maintains itself by the energy it picks up in the form of water vapor from the tropical sea or ocean. It differs from a tornado in many respects but chiefly in its extent. A hurricane usually has a diameter of 400 to 600 miles with a relatively calm area at the center 15 to 30 miles in diameter. Associated winds may vary from 8 miles per hour to more than 125 miles per hour. From the air, an approaching hurricane looks like a typical warm front except that the approaching edge of the cirrus clouds is more circular. As the center is approached, ceilings and visibilities come down, precipitation increases, turbulence increases, and flying becomes more uncomfortable and hazardous.

c. Movement.—In the Tropics of the Northern Hemisphere, hurricanes move west and west-northwest with the direction and velocity of the prevailing winds. At about 23½° latitude, they curve northward then move to the east under the influence of the earth's rotation. Exceptions to this general movement occur, especially in the middle latitudes. A pressure trough or strong front to the west of a hurricane will attract the hurricane and cause its course to be more northerly with possibly a westward component. The rules for the movement of pressure centers apply to hurricanes.

d. Dissipation.—Movement over land quickly destroys the intensity of a hurricane. Four hours over land causes a great decrease in strength and hurricanes have disappeared entirely before 12 hours over land have elapsed. Frequently they continue on through the middle latitudes as extra-tropical cyclones. A water trajectory, especially over the Gulf Stream, helps to maintain their intensity.

SECTION XIV

ICING OF AIRCRAFT

118. Physical process.—The formation of ice on aircraft results from the freezing of water upon surfaces of an airplane. This apparently simple process involves such various factors as condensation, solidification, evaporation, and sublimation, all of which are dependent in part upon temperature and humidity. Water vapor changes from the gaseous to the liquid state by condensation upon nuclei which are chiefly sea salt particles but may be air molecules, dust, or smoke particles. The heat of condensation, about 600 cal./cc., is released upon condensation of water vapor. When the water freezes, it changes from the liquid to the solid state and releases about 80 cal./cc., this being known as the heat of fusion. Sublimation occurs when the water changes directly from the gaseous to the solid state and is accomplished by the release of the sum of the above two amounts of heat. The reverse of these three processes absorbs heat in like amounts.

119. Supercooled water.—Supercooled water exists in supercooled water clouds and in supercooled rain. In the majority of cases, icing occurs in supercooled water clouds, very rarely in supercooled rain. Ice clouds, that is, clouds containing only ice crystals, present no icing hazard. The small particles do not stick to the surfaces of an airplane. Water clouds are the result of condensation of water vapor contained in the air upon condensation nuclei, which are very minute particles of hygroscopic substances of several hundred-thousandths of a millimeter in diameter, normally fluid. Water clouds can form at temperatures above zero as well as at much lower temperatures. As the temperature decreases from 0° C., the formation of water clouds becomes continually less probable while the probability of the formation of ice clouds increases. Ice clouds are formed by the sublimation of water vapor upon sublimation nuclei which, in contrast to condensation nuclei, are solid and insoluble in water. Below about −15° C. to −20° C, ice clouds form instead of water clouds provided sublimation nuclei are present. The fact that liquid water exists in the atmosphere at temperatures below freezing is of prime importance in ice formation on an airplane. Such water is known as supercooled water. Various explanations have been offered for this phenomenon but none of them appear to be completely satisfactory. One states that since the condensation nuclei are salts, the freezing temperature will be lowered. Another offers the idea

that the hail stage, which is left out of current thermodynamical diagrams, may assume rather great thicknesses. In any event, it seems reasonable to believe that the arrangement of the molecular aggregates in water droplets may be retarded in some way so that they cannot assume the arrangement required for solidification. The fact remains that water can persist in the atmosphere as liquid droplets at temperatures as low as $-40°$ C. These facts and ideas allow the reasonable conclusion that the agitation of supercooled drops caused by striking an airplane may cause their solidification.

120. Types of ice.—*a. Clear ice* is a clear, hard, amorphous ice. It is the most important type of ice for the pilot to consider. It

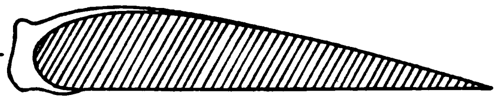


FIGURE 150.—Clear ice on an airfoil.

forms a blunt nose on the wing as shown in figure 150, adds weight, reduces the aerodynamic efficiency of the wing, and thereby reduces the lift. Clear ice may form at temperatures from 0° C. to $-22°$ C. About 80 percent of the clear ice forms at temperatures of $-8°$ C. or higher.

b. Rime is an opaque, whitish ice with a granular texture. It is not so tenacious in its formation on an airfoil and does not destroy the

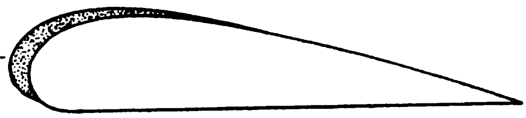


FIGURE 151.—Rime on an airfoil.

characteristics of the airfoil, but it may add considerable weight. Rime may form at temperatures from 0° C. to $-30°$ C. Only about 55 percent of the rime that occurs forms at temperatures below $-8°$ C. Usually, heavy coatings of ice on aircraft consist of both rime and clear ice.

c. Frost is small separate crystals of ice. Frost is of little importance in the icing of aircraft while in flight. However, frost deposits on parked airplanes should be cleaned off before take-off as they may inhibit action of the controls, especially during take-off.

121. Aircraft ice formation theory.—Various ideas have been presented to account for the formation of ice on aircraft. The following theory is now generally accepted:

a. Let it be assumed that 1 cubic centimeter of liquid water exists in the atmosphere at a temperature of $-8°$ C., the temperature of the

free air. This water must freeze at 0° C. and since 1 calorie of heat is required to raise 1 cubic centimeter of water 1° C., it will require 8 calories of heat to raise this amount of water to 0° C. In order for any portion of the cubic centimeter of water to freeze, it must release its share of the 80 calorie heat of fusion. Therefore the freezing of $\frac{1}{10}$ of the cubic centimeter will release the amount of heat necessary to raise the entire cubic centimeter to 0° C. and leave the remaining $\frac{9}{10}$ of the cubic centimeter as liquid water at 0° C. to be blown back over the airfoil. The higher the temperature of water, the greater its vapor pressure or tendency to evaporate. The water being blown back over the airfoil, now has a temperature of 8° C. higher than that of the vapor in the surrounding air. Thus the initial ice formation facilitates the evaporation of the remaining $\frac{9}{10}$ of the cubic centimeter. This evaporation is also aided by the greatly reduced pressure at the upper forward surface of the airfoil. The release of 72 calories of heat is all that is required to freeze the entire remaining portion of the original cubic centimeter. 72 divided by 600 gives the portion of the original cubic centimeter that must be evaporated in order to freeze $\frac{9}{10}$ of the cubic centimeter. If we assume that the entire $\frac{9}{10}$ of the cubic centimeter will not be frozen because of evaporation of part of the amount, it becomes evident that about $\frac{1}{8}$ of the unfrozen portion of the original cubic centimeter must evaporate to freeze the remainder of this portion. Under the conditions specified above, it is assumed that this will be accomplished in a very short space of time thereby causing $\frac{3}{4}$ of the original cubic centimeter to be frozen shortly after impact upon the airfoil. This freezing process is further aided by the fact that the relative humidity in clouds is usually less than 100 percent.

b. When the majority of the water droplets freeze upon impact, rime is formed. This is more likely to occur, the lower the temperature and the smaller the size of the water droplets. The size of the droplets is believed to be the controlling factor, hence small droplets will form rime and large ones will form clear ice.

c. In the atmosphere, there frequently exists supercooled rain or clouds containing supercooled droplets of water. Upon contact with the airplane, the supercooled water, whether it be in the form of rain or cloud droplets, congeals, producing ice.

d. The supercooled rain, formed of large drops which spread out in striking the airplane, gives rise to a layer of solid transparent ice.

e. The clouds of supercooled water give, according to size of the droplets of which they are composed and according to their temperature, clear ice or rime, or commonly a combination of both. The

thickness of the layer of ice produced may be considerable. In 2 or 3 minutes, a dangerous layer of ice several centimeters in thickness may be produced. In estimating the temperature of a cloud, the indicated free air temperature must not be relied upon too rigidly after ice begins to form upon the exposed temperature element since an erroneous reading may be caused by the absorption of the latent heat of fusion of the water by the temperature element.

122. Factors influencing formation of ice.—The rate of deposition of ice depends on—

a. The mass of liquid water traversed per minute by the airplane.—(1) The rate of deposition is greater, the greater the speed of the airplane. A free balloon, moving with the wind, rarely experiences icing. Captive balloons and kites exposed to prevailing winds undergo serious icing only when exposed to the falling of supercooled rain.

(2) The more liquid water a cloud contains, the more rapid the rate of deposition. The amount of water in a cloud may be roughly judged by the visibility within the cloud. The more water the cloud contains, the less the visibility within the cloud.

b. The rate of freezing of supercooled water.—(1) The importance of the rate of freezing of supercooled water increases from 0 to about −8° C. and then diminishes to become insignificant at very low temperatures. Melting ice is usually very slick and smooth but ice without a film of water is a very sticky, tenacious substance. Clear ice is much more sticky than rime and clings very tenaciously to even a smooth surface.

(2) As the temperature decreases, the ice becomes less and less compact and tenacious. Below −12° C., rime is usually formed which is very brittle and contains many interstices which make it subject to the effects of wind and vibration. The ice that is the most serious and the most adherent is formed at air temperatures between 0 and −8° C.

c. Form of the body.—A body presenting a rough surface ices more readily than a body with a polished surface.

d. Size of the droplet.—The larger the droplet, the more readily clear ice forms. The smaller the droplet, the more readily rime forms.

123. Icing in clouds.—Icing of aircraft may take place in any cloud which contains supercooled water droplets. In general, icing is more severe in cumuliform clouds than in stratiform clouds.

a. In cumuliform clouds.—The vertical motions, which give cumuliform clouds their characteristic appearance, support large droplets and make the formation of clear ice more frequent in this type of cloud. Cumuliform clouds form in unstable air. Therefore, clear ice is more

likely to form in clouds in unstable air than in stable air. The instability may be due to steep lapse rates or mechanical turbulence caused by large vertical velocity gradients. Mountains may have some effect in producing instability within an air mass by causing the potentially unstable air to be lifted to its saturation level. Tg air is often characterized by its potential instability; hence, the combination of temperatures near freezing, Tg air with its large water content, and mountains is almost sure to produce icing conditions. This combination of factors occurs in winter, particularly over the Appalachian Mountains. In winter, Pp air contains considerable moisture in its lower levels by the time it reaches our Pacific coast and is also unstable in the lower levels. When Pp air crosses the Cascade, Sierra Nevada, and Rocky Mountains, serious icing conditions frequently result. The formation of supercooled water in the atmosphere may perhaps be understood

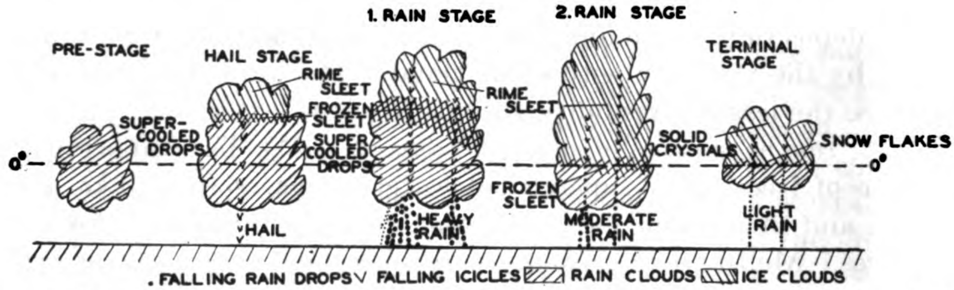


FIGURE 152.—Distribution of ice and water cloud layers in the progressive stages of development of a cumulonimbus cloud.

by considering the condensation and sublimation products formed in a cumuliform cloud. The ice and water cloud layers in the formative stages of a cumulonimbus cloud are shown in figure 152. The small cumulus cloud formed first consists of water droplets only, hence is a supercooled water cloud above the 0° C. boundary (dashed line in fig. 152). On further growth, the ascending air current reaches the critical temperature where sublimation upon the sublimation nuclei begins. From then on only ice crystals are formed. The supercooled water droplets, carried by the rising air current into the uppermost part of the cloud, evaporate quickly and the water is redeposited upon the ice crystals as ice, because the water vapor absorption capacity of ice crystals at low temperatures is considerably greater than that of water droplets. In the zone where supercooled water droplets occur along with ice crystals, the ice crystals grow rapidly by the addition of ice from the transformed water of the water droplets. When the grains of ice cannot be held up any longer by the rising air currents, they drop. On dropping through the broad layer containing the supercooled water droplets, the ice crystals grow still more in the same

fashion as the leading edges of an airplane are coated with an ice layer by such a supercooled water cloud. Thus hailstones are formed. Through the continuous descent of ice crystals, the supercooled water droplets are gradually eliminated. The supercooled water cloud disappears, but the ice cloud pushes down from above to take its place. Soon the dropping ice particles are unable to grow as fast as before. Remaining smaller, they melt on dropping below the 0° C. boundary and form raindrops. With the progressive shrinkage of the water cloud, the rain intensity gradually abates. From the course of the precipitation, the formative stages of the cumulonimbus cloud can at any time be recognized, hence the stratification of ice and water clouds and the position of the zone of ice formation can be determined.

b. In stratiform clouds.—(1) The principles given in *a* above can also be used for stratiform clouds as illustrated in figure 153. No

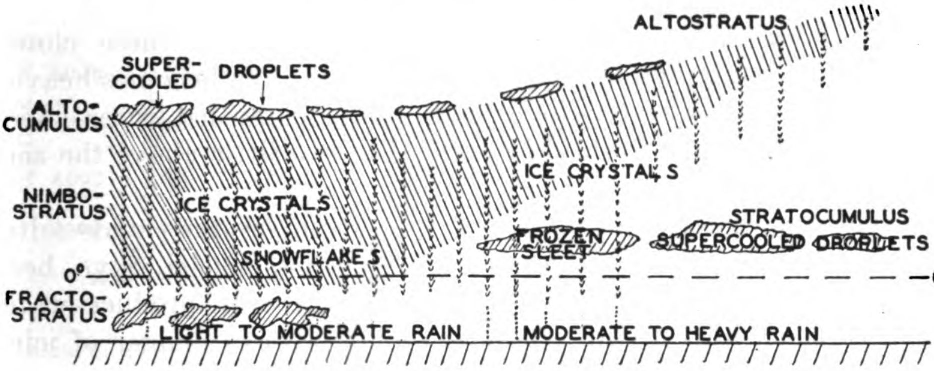


FIGURE 153.—Stratiform ice and water clouds (formative stages of nimbostratus).

normal rain falls from water clouds. They may produce a drizzling rain which, however, will not fall to the ground unless the clouds are low and the humidity is high. For this reason, the stratocumuli in figure 153 are not causing rain. From the absence of rain, it can be concluded, from the ground, that these clouds are water clouds in which icing conditions must be present because they lie above the 0° C. boundary. The altostratus clouds shown cause no precipitation at the ground because their lower edges are very high and the falling ice crystals evaporate in the dry layer below them. Through the continued falling of ice crystals, the air below the altostratus becomes more and more humid and the lower boundary of the ice cloud sinks from right to left (fig. 153). Ultimately the ice crystals reach the supercooled water clouds where they quickly form ice pellets, fall rapidly, and finally turn to raindrops. The start of a moderate or heavy rain on the ground is typical of the cloud stratification shown in figure 153. At the same time, it indicates the dissolution of the supercooled water clouds.

(2) The rain stops temporarily or at least slackens. The ice crystal cloud continues to sink on account of the falling motion of the crystals and finally reaches the zero level. Then the altostratus becomes a nimbostratus; fundamentally both types of clouds are identical. Near the zero boundary the ice crystals combine to form snowflakes which, during further fall, melt into raindrops and result in a light to moderate rain. In winter, when the zero level is low or below the ground's surface, the snowflakes do not melt and the snow reaches the ground. The lower level of the nimbostratus, the true rain cloud, lies near the 0° C. boundary, since below that level, all small ice crystals must melt. Below the nimbostratus new water clouds are almost always formed because of convections. The high humidity underneath the rain cloud allows new clouds to form readily. These lower tattered clouds (fractostratus or fractocumulus) produce no precipitation, but increase the intensity of the rain if they extend above the zero level. The ice crystals dropping through these clouds become much larger and the rain on the ground then becomes heavier for a while. This indicates the formation of supercooled water clouds and the existence of a fresh icing layer that is a little above the zero level.

(3) The upper level of the ice crystal cloud, water clouds (altocumuli) are often formed because sublimation nuclei have been carried away and new vertical movements can only produce water clouds. On account of this, there is almost always danger of icing in the uppermost layer of the rain cloud. Although the altocumulus layer is usually about 200 to 300 meters thick, it may occasionally extend for 1,000 meters or more. This condition exists in clouds from which rain has fallen for a considerable period of time and from which only a little rain is falling. It is apparent that dependable precipitation records give a very satisfactory indication of the ice and water cloud layers.

(4) Rime may be expected more frequently in stratiform clouds than in cumuliform clouds. Vertical motions are at a minimum in stratiform clouds or else they would not maintain their stratiform appearance. Since vertical motions aid in the formation of large drops, the drops in stratiform clouds are usually smaller and when struck by an airfoil they freeze upon impact to form rime. Thick stratiform clouds are more conducive to clear ice than thin ones.

c. Along fronts.—(1) About 85 percent of the observed icing of aircraft occurs in frontal zones. Typical warm front clouds are stratiform in character and rapid movement up the warm front may contain only a small vertical component, but the small lift of a great

mass of warm air may produce thick cloud systems and heavy precipitation with larger drops than otherwise might be expected from stratiform clouds. The potential instability of the warm mass may be released to form cumuliform clouds. Clear ice or a combination of clear ice and rime may result. Warm front cloud systems are often of great extent, thereby causing flights in them to be of long duration with a subsequent increased danger of severe icing.

(2) The overrunning warm air may be above 0° C. in the lower levels and thus prevent icing in that region. If clouds in the warm air are thick and the temperature just above the frontal surface is only a few degrees above zero, the upper portion of this cloud system may

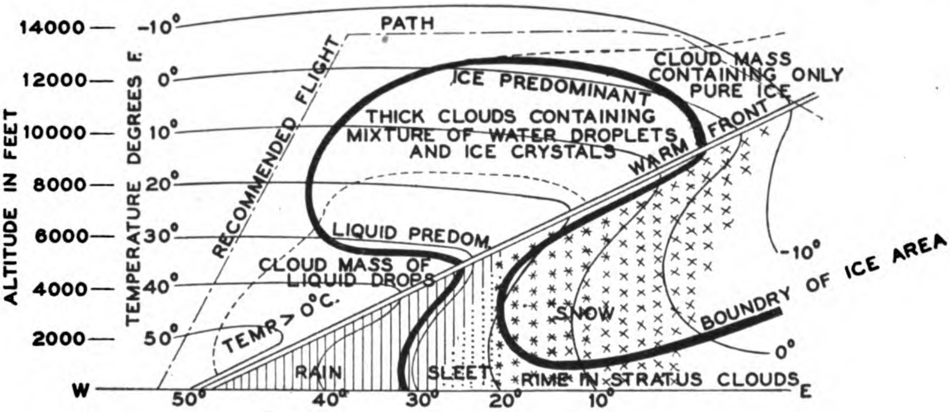


FIGURE 154.—Warm front icing situation.

well be considerably below 0° C., thus providing a transition zone within the cloud system that is conducive to icing.

(3) Cold fronts are associated with cumuliform clouds and are more likely to cause clear ice. The cold front cloud system is relatively narrow compared to the warm front system so that the period during which icing may take place on a flight across the frontal zone is shorter. However, the combination of clear ice and a higher rate of accumulation makes cold front icing zones extremely hazardous.

d. Appearance of clouds.—Observation of the clouds offers substantial aid in the determination of icing zones. Ice and water clouds exhibit characteristic differences in their appearance. With some experience in observation, from the ground or from an airplane, it can be reliably ascertained whether a cloud contains ice crystals or water droplets or both, when the level of the 0° C. boundary is known. The pilot usually has the opportunity to determine the location of this level with extreme accuracy. With this information at hand, he can tell whether a cloud presents an icing hazard or not. The ice clouds contain fewer but larger particles than the water clouds. Hence they

are optically thinner and appear sometimes merely like heavy mist. Their borders are hazy because the large particles drop rapidly and evaporate more slowly outside the clouds than the much smaller water drops. Water clouds are sharply outlined, particularly if they are growing. When the clear cut contours and the cauliflower appearance of a cloud start to become indistinct and hazy, and when the overall appearance of the cloud becomes fibrous in character, the change of a water cloud to an ice and water or ice cloud is indicated.

e. Reclassification of clouds.—The old but improved method of classifying clouds according to form and height affords no safe criteria

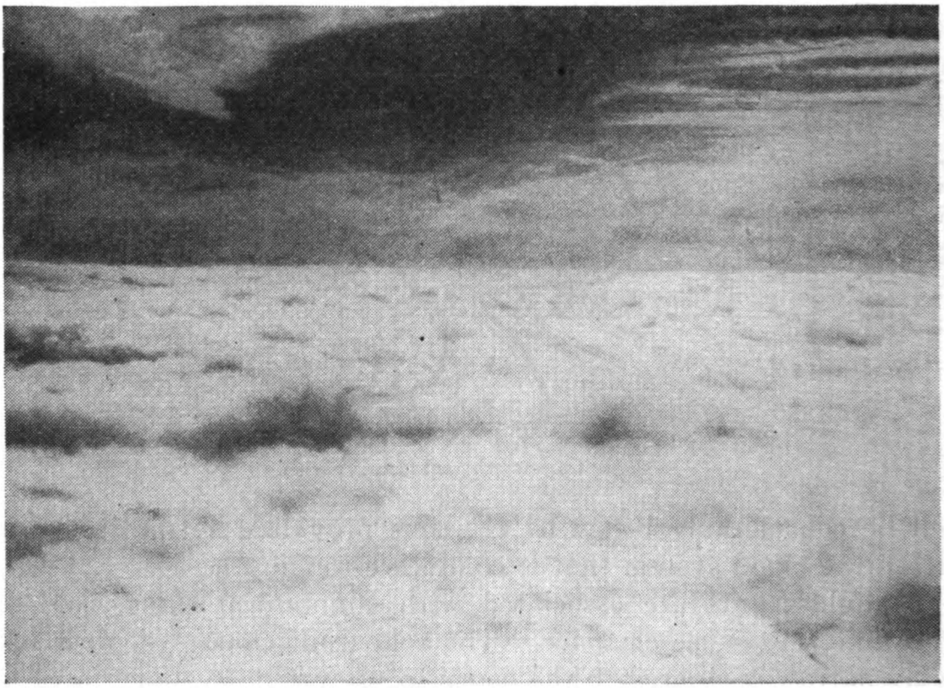


FIGURE 155.—Top of a stratified water cloud (stratocumulus).

for distinction between ice and water clouds. When new viewpoints are applied to the known classification, the following should be fundamentally classified as ice clouds: Cirrus, cirrostratus, altostratus, and nimbostratus; as ice and water clouds: cumulonimbus and altocumulus. In very cold weather, stratocumulus and cumulus may occasionally consist wholly of ice crystals. Generally, all other clouds are water clouds throughout. Ice particles from some other source may on occasion drop through these clouds. Figures 155, 156, and 157 show the typical differences in the appearance of ice and water clouds.

f. Effect of speed on zero boundary.—To estimate whether icing is imminent in a cloud requires knowledge of the temperature as well

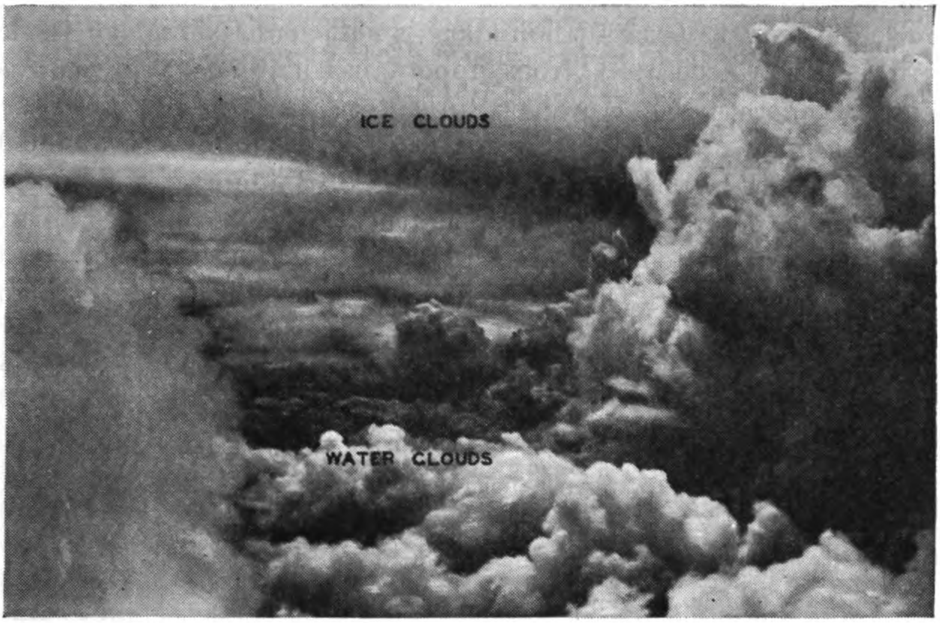


FIGURE 156.—Lower edge of a stratified ice cloud with water clouds beneath (altostratus above, cumulus below).

FIGURE 157.—Cloud containing both water and ice particles (cumulonimbus). Severe thunderstorm in progress.

as the determination of the particle type. As far as the pilot is concerned, the height of the 0° boundary is sufficient. This can be determined fairly accurately from upper air soundings and reported ground temperatures. However, in forecasting the 0° boundary from the ground, it is absolutely essential to bear in mind that the 0° level varies with airplane speed. Because of the impact and friction of the air on the airplane, the temperature of the airplane is always higher than the air temperature and the differential increases as the airplane speed increases. Due to this fact, the 0° level of an airplane in flight is always higher than the meteorological 0° level. In cloud flying at altitudes between 3,000 and 7,000 feet, the following figures are applicable:

Flying speed (miles per hour)	100	150	200	250	300
Approximate lifting of 0° boundary (feet)	350	800	1,500	2,350	3,400

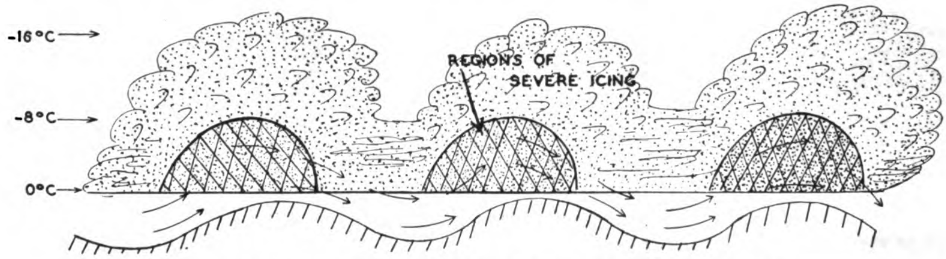


FIGURE 158.—Section across parallel ridges showing most dangerous icing areas.

The conventional types of airplanes today reach the 0° C. level, and hence the base of icing layers, at heights which are at least 600 feet above the meteorological zero level. This effect is especially favorable for high-speed airplanes. During flight, the pilot should watch the free-air temperature closely and remember that it does not indicate the meteorological but the increased temperature. Since the temperature rise in flight through a cloud is about 40 percent lower than outside of it, he must, before flying into dangerous ice clouds, seek an altitude where the thermometer depending upon flying speed reads at least 0.5° to 2° C. above zero.

g. Over mountains.—(1) Icing is more probable and more severe in mountainous areas. Mountain ranges cause upward motions on their windward side in air that is moving across them. Vertical motions over the ridges will support large droplets. The most severe icing will take place above the crests and to the windward side of the ridges.

(2) The movement of a front across mountains brings together two important factors that aid in the formation of icing zones. A study of icing in the western United States has shown that almost all of the

ice cases occurred where the air was blowing over a mountain slope or up a frontal surface or both.

(3) The general north-south orientation of mountain ranges in the United States presents their western flanks to the prevailing westerlies of the middle latitudes. The instability of any potentially unstable air may be released by the lift acquired.

(4) Due to their elevation, mountainous areas aid the formation of icing zones during a greater portion of the year than flat country. Icing zones in mountains frequently are not as easily avoided as over smooth terrain. The zero and saturation levels are below the tops of ridges, even in daytime, whereas there is usually some ceiling below icing zones over flat country during the day and even at night.

h. Air masses.—The large majority of icing cases occurs in winter in Pc air that has crossed the Great Lakes, Tg air over the Appalachian Mountains and in fresh Pp air that is crossing the Cascade, Sierra Nevada, or Rocky Mountains. These three air masses are potentially unstable (unstable for the saturated state), Pp throughout about 2 kilometers, Tg to about 5 kilometers, and Pc for about 1½ kilometers, by the time they reach the areas mentioned. The vast majority of icing in Pp air takes place in air that is less than 3 days from its source region. Tg air that is modified Pc air which has been "conditioned" by a brief trajectory over the South Atlantic Ocean or the Gulf of Mexico has the highest degree of potential instability and is conducive to severe icing in the upper levels. RPc that has been modified by rain from Tg often contains icing zones, especially when ahead of a secondary cold front. The safest method by which to fly over a mountainous area in which icing zones exist is to fly over the top. When this is impossible, the relation of temperature, fronts, mountains, winds, and air masses must be determined in order to avoid icing layers. This may necessitate flight beyond the destination in order to find a suitable place to let down.

i. Zones.—Lifting by some method was taking place in all recorded cases of icing. Strong winds are conducive to heavy icing zones. However, the determination of icing zones on the basis of the available station reports and on the basis of the weather map must rely on the precipitation and cloud observations of the individual stations. Just as precipitation and clouds in different places are usually different, positions of icing zones vary. Uniform location and range of icing zones over extended regions are rare. Moreover, the icing zones are not tied in simple fashion to fronts or air masses. The icing hazard is often least in extended precipitation zones. Supercooled rain occurs occasionally in precipitation zones which have a marked

temperature stratification, but the icing hazard in supercooled rain is not very great so long as the flight through it is not protracted. The amount of water contained in air in supercooled rain is substantially less than in the supercooled clouds. Even the vertical height of the icing zone is usually small in supercooled rain and can be readily predicted. The pilot can avoid icing zones and the icing hazard in most cases by using this information during flight. He should be particularly careful about the altitudes at which he flies when near icing zones. The layers in which icing may occur are

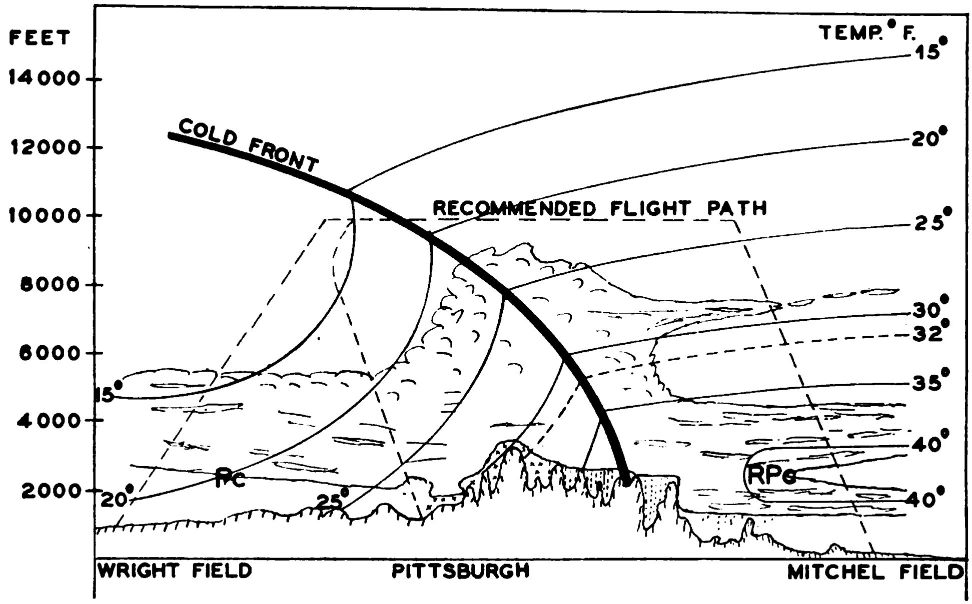


FIGURE 159.—Recommended paths between Wright Field, Pittsburgh, and Mitchel Field with Pc cold front over the Appalachian Mountains.

usually restricted both vertically and horizontally. Their location can be ascertained with sufficient accuracy before take-off.

124. Icing hazards.—Icing of an airplane causes the following serious or even dangerous hazards:

a. Icing of the leading edges and the surfaces of an airfoil causes a deformation of profile which reduces the lift.

b. Icing increases the weight.

c. Icing increases the drag.

d. Icing may destroy the equilibrium of the propeller and cause vibrations. It may freeze the controllable pitch mechanism of the hub.

e. The control surfaces may be jammed or frozen tight and thus prevent pilotage.

f. Retractable landing gear may become jammed.

g. Ice deposits on cockpit windows may prevent forward visibility.

h. Radio reception and transmission are interrupted. Iced antennae and radio masts may be blown down.

i. Air speed meters and venturi operated flight instruments may become useless.

j. Ice thrown from the propellers may cause structural damage.

125. Methods of ice protection.—Four methods of ice protection may be employed as follows:

a. Thermal.—These consist of heating the exposed parts by heat generated through electrical resistance or by heat from the exhaust gases. Only small mechanisms such as the exposed portion of flight and navigation instruments and the radio antenna may be protected by these means since the amount of heat required for larger surfaces is prohibitive. It is probably not necessary to melt all the ice that is formed, as liquefaction of the surface of the ice in immediate contact with the airplane renders the rest of the deposit less adherent and more detachable by the wind and the normal vibrations of the airplane.

b. Mechanical.—Vibrations do not prevent the formation of ice but they cause the ice to break from the contact surfaces. This principle is used in most de-icers that employ a pneumatic covering for the leading edges. Alternate inflation and deflation by air of the rubber covering cause the ice to crack and be blown away by the wind.

c. Chemical.—These consist of coating the surface with a thick oil or varnish which prevents the adherence of the ice. The chemical coating must be constantly renewed in flight due to the scouring effect of wind and precipitation. These means are employed chiefly to prevent the formation of ice on propellers. Oil vents in the propeller hub allow a small quantity of oil to continually stream over the propeller blades.

d. Weather forecasting.—The principal task of the forecaster must be to inform the pilot of the zones in which there is danger of icing and the position of the isothermal surfaces of 0° C. in relation to the cloud layers. In arriving at his conclusions, the forecaster must make use of available upper air soundings, structure of the air masses involved, frontal relationships, and knowledge of the terrain. The pilot may forecast for himself by remembering the synoptic situation, noting the type of clouds to be encountered, observing the indicated temperature, correlating recorded ground temperatures with the average lapse rate of the air mass in which he is flying, and considering terrain features.

126. Practical rules and conclusions.

a. Severe icing usually occurs in clouds.

b. Get out of the clouds.

c. Going above the clouds will stop ice formation and evaporate existing ice slowly.

d. Going below the clouds may increase the temperature to above 0° C., but it may also lead to a region in which subcooled rain is falling.

e. Icing is most frequent and severe in frontal zones.

f. The larger the droplets the more likely clear ice will form.

g. The stronger the vertical currents and the more dense the cloud, the more water the cloud will contain and the more likely clear ice will form.

h. The maximum vertical motions occur in cumuliform clouds.

i. Sometimes at low temperatures in a thick cloud, no ice will form because the cloud particles are ice crystals already.

j. In TG and PP air with cumuliform clouds and the right temperatures, clear ice is almost certain to form.

k. Mountains increase vertical currents, hence aid in the formation of severe icing conditions.

l. Wherever stability exists in clouds through which rain is not falling, the droplets are small and rime may be expected.

m. Clear ice usually forms in maritime air masses.

n. Rime occurs about four times as often as clear ice.

o. Rime is less tenacious than clear ice and responds more readily to the action of de-icers.

p. Know where the zero level is.

q. High-speed airplanes have a higher zero level than slow airplanes.

SECTION XV

TERRAIN EFFECTS

127. General.—The distribution of land and water over the earth's surface has a marked effect on the general circulation of the atmosphere. In winter, from the middle latitudes northward, land areas are usually

colder than ocean areas. Hence, during the winter season, large high-pressure areas persist over land and large low-pressure areas remain over water. The accentuated temperature differential between these two types of surfaces causes the winter circulation to be more intense than that in summer. During summer, land areas are generally warmer than the oceans, hence during this season, Lows exist over land and HIGHS over the ocean.

128. Monsoons.—*a*. A monsoon condition exists where a complete reversal of air flow takes place between winter and summer with such a cycle occurring once a year. The monsoon effect is important in many places, the most notable being in India where the prevailing wind is offshore in winter and the warm moist air from the Indian Ocean moves onshore during the summer. This accounts for the abnormally large amount of precipitation in India during the summer.

b. In the Gulf region of the United States, the prevailing wind is offshore during the winter due to outbreaks from the Canadian and Great Basin HIGHS. The winter monsoon forces the Gulf air to the south and carries either the extremely cold air from Canada or brings the clear air from the Pacific to the Central, Southern, and Eastern States. The general offshore drift is frequently interrupted by a return flow from the Gulf. This reverse flow in winter brings either TG air or some air mass that is approaching TG in its characteristics. The most severe weather results from the interaction between returning masses and the outbreaks from the North. In summer, the land areas in the United States are warmer on the average than the Gulf of Mexico so that the flow is reversed during this season thereby causing a typical monsoon condition. PC air becomes slightly unstable in the lower levels as it moves far to the south over land that is free from ice and snow. Figure 160 indicates the rapid increase in thickness of the unstable layer as it moves over the Gulf of Mexico in winter.

c. The average extent of TG air over the United States is much greater in summer than in winter. Midsummer thunderstorms along the Pacific coast occur in TG air that has been forced far west of its normal trajectory by a westward extension of the Bermuda HIGH. Southern and Southeastern States are almost continually occupied by TG air in summer. Frequently it moves as far north as Canada during this season. The extent of the TG air determines where showers and thunderstorms may be expected in summer.

d. Monsoon winds from the ocean are cooler than adjacent land areas. Over land, the air becomes unstable through the excessive heating of the lower layers. Instability phenomena such as bumpiness, cumulus clouds, showers, and thunderstorms occur in the air

from the ocean when it forms a thick layer. The summer monsoon in India attains a thickness of about 30,000 feet.

e. The coast of California is also affected by monsoon flow. During winter, the Great Basin HIGH frequently causes offshore winds with resultant clear weather and unusually high temperatures. Adiabatic heating of air flowing out from the Great Basin provides the chief

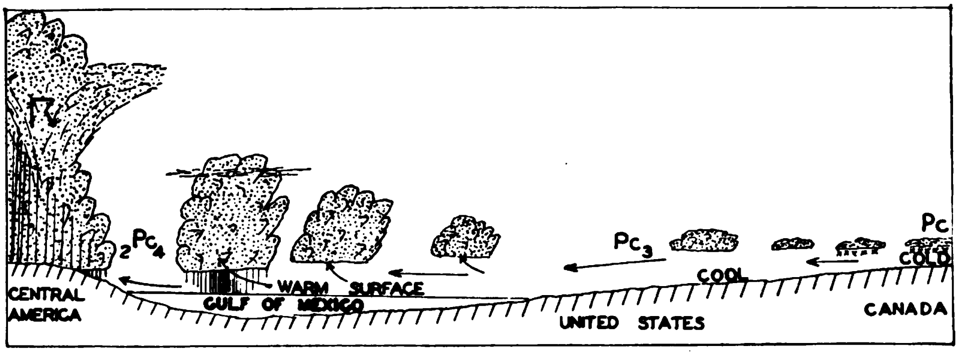


FIGURE 160.—Winter monsoon of Pc air across the Gulf of Mexico.

contributing cause of the mild winter climate of southern California. During summer, the interior land areas are much warmer than the adjacent Pacific resulting in a persistent sea breeze. Since ocean temperatures off the Pacific coast are between 50° F. and 60° F. during the entire year, the coastal regions are unusually cool during

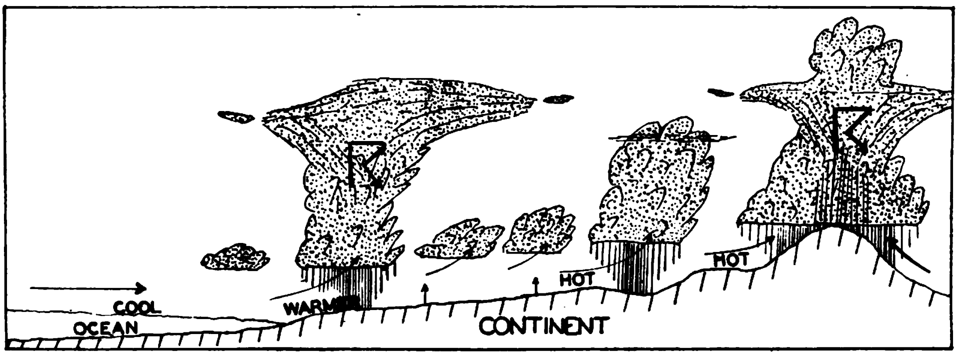


FIGURE 161.—Instability phenomena in thick summer monsoon.

the summer and relatively warm during the winter. Areas along the Pacific coast experience similar temperatures during both winter and summer. The sea breeze on the Pacific coast of the United States in summer is so shallow that showers cannot develop. The thick currents from the west are too dry and stable for clouds to form in them except along the higher mountain ranges. Showers in summer are rare.

129. Land and sea breezes.—*a.* In addition to the seasonal con-

trast of temperature between land and water, there is also a daily reversal of the temperature gradient which produces a similar but more local effect than the seasonal one. The local effect is most pronounced in summer because the diurnal variation in temperature over land is greatest then. During the day, the land is warmer than the ocean, while at night, the ocean is warmer than the land. Adjacent cold and warm sources are provided and the wind moves in accordance with the circulation principle. It blows from the sea to the land in the daytime to form the sea breeze, and from the land to the sea at night to form the land breeze. These winds are shallow and do not penetrate far inland when they do not coincide with the general air movements. The sea breeze is considerably stronger than the land breeze, sometimes attaining velocities up to 30 miles per hour. Land and sea breezes are more pronounced in tropical regions than in the higher latitudes where they are often submerged by the stronger winds of a more general nature.

b. Along the Pacific coast, particularly in California, the sea breeze in summer has a pronounced effect on flying activities. This wind brings in the moist air from the Pacific Ocean that causes the persistent low stratus and fog of that area. This layer is usually about 1,000 feet thick and is much colder than the warm air of the interior. The strong inversion produced confines the sea breeze to the lower levels and forces the stratus clouds or fog down on any ground that is much higher than sea level. The average velocity of the sea breeze through the Golden Gate at the entrance to San Francisco Bay during the early afternoon in July is about 25 miles per hour. Along the Gulf coast in summer, the sea breeze is aided by the general monsoon effect and penetrates much farther inland than on the West coast. The sea breeze on the Atlantic coast is less pronounced because it is opposed to the general air movement.

c. The front edge of the sea breeze may often be observed in the form of a distinct haze line that progresses inland during the day. Summer fog and low stratus do not form at stations that have not been passed by the sea-breeze front. When the sea-breeze air stagnates in a local area such as the Los Angeles Basin for several days, it becomes very hazy and visibilities may be reduced to 1 mile or less. The vertical visibility is better than the horizontal visibility. This makes it possible to fly "contact" when the horizontal visibility is, for all practical purposes, zero.

130. Mountain ranges.—Minor irregularities exist over any continent or land area. These irregularities may be mountains, valleys, and gradual land slopes. Their effect is usually directly propor-

tional to their size although small irregularities may cause unusual local effects.

a. Effects on stable air.—(1) The stability of the air is of great importance when considering the flow about mountains. Stable air will resist a change of level unless the pressure gradient is sufficient to overcome the barrier effect of the mountain ranges. Stable air tends to diverge and flow around a mountain barrier.

(2) This effect is often particularly noticeable in fog movements. An advective fog will first fill up the valleys and often leave the surrounding hilltops exposed. The air terminal at Burbank, Calif., is frequently protected from fog by the Hollywood hills. Another example exists in the San Francisco Bay area where the sea breeze coming in through the Golden Gate diverges over the bay and one portion runs north giving southerly winds at Hamilton Field, while

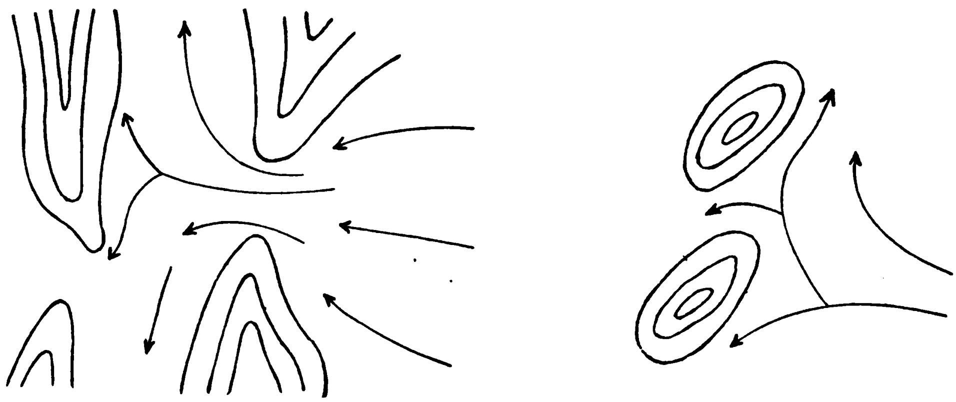


FIGURE 162.—Stable air flow around mountains.

another portion moves southward producing northerly winds at Sunnyvale.

(3) The damming effect of mountain ranges produces an increase of pressure gradient on the windward side and a decrease of pressure on the leeward side. This is frequently shown by the flow of Pc air in central North America. The Rocky Mountains and the mountain ranges of Alaska usually keep the Pc masses to the east and as a result a large pressure gradient is built up along the Continental Divide. The high pressure gradient produced represents potential energy and hence has no effect on winds. The action of these mountains might be compared to that of a vertical glass plate between heavy and light liquids in a basin. No motion takes place until the plate is removed.

(4) Stability of the air tends to prevent precipitation even if the air is lifted over mountains except that there may be mist or drizzle.

b. Effects on unstable air.—The lifting of unstable air over mountains usually causes heavy precipitation and always heavy clouds.

Unstable air does not resist vertical motions, hence mountains do not form an effective barrier to the movements of unstable air.

c. Foehn winds.—Winds blowing down the lee slope of a mountain are adiabatically heated and when the flow is of some magnitude it is known as a "foehn" wind. The typical cycle of a foehn wind consists of flow up the windward side with resultant precipitation and the

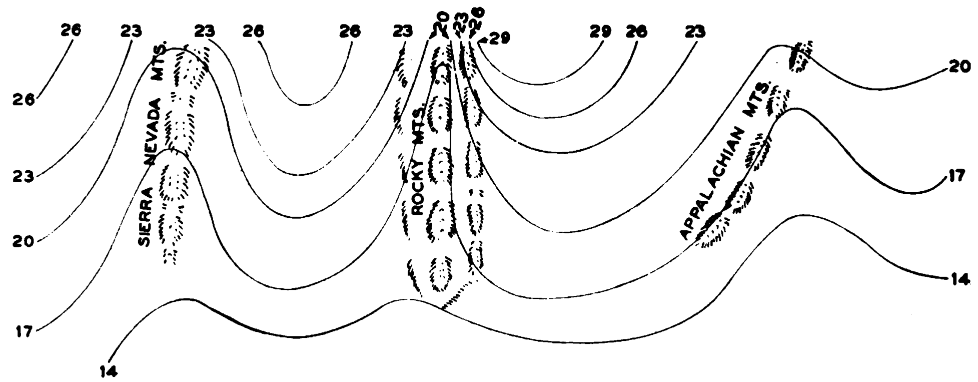


FIGURE 163.—Pressure gradient caused by a mountain range.

addition of the heat of vaporization to the surrounding air. Consequently, when the air descends on the leeward side, its temperature at any given level is higher than on the windward side. The Chinook wind is a local name for the foehn winds that come down off the Rocky Mountains. The Great Basin HIGH causes foehn winds in the surrounding areas and the effects of these winds are felt from Washington to Florida. Foehn winds that move into southern California are about 27° F. warmer at the surface than they were in the Great Basin.

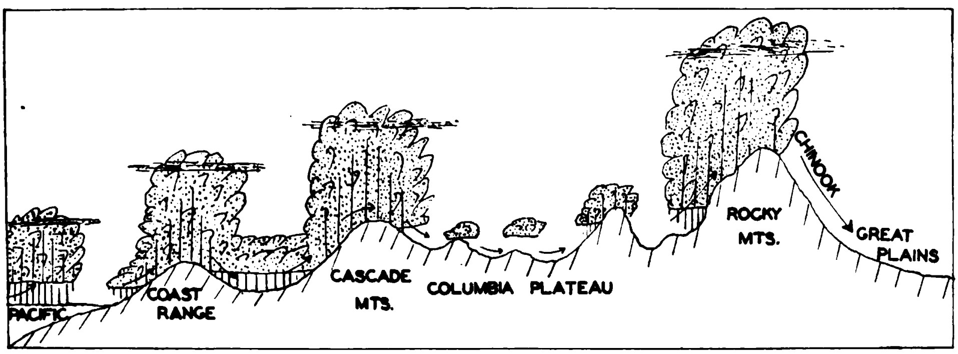


FIGURE 164.—Mountain effects on eastward moving Pp air in winter.

d. Effects on approaching fronts.—(1) Mountain ranges cause prefrontal rain due to the lift required to force the air over the mountains. Examples exist in the flow of Tg, Ta, and Pc across the Appalachian Mountains and the flow of Pp or Tp over the mountain

ranges of the Western States. When westerly winds strike the west coast, precipitation is caused, first by the coast ranges, and later by the Cascade and Sierra Nevada Mountains that are higher than the coast ranges. The air remains unsaturated over the Great Basin and surrounding areas causing the deserts in this region. When the air is lifted over the Rocky Mountains to higher elevations than it has been previously, clouds and precipitation again occur. Pp or Tp air do not cause precipitation east of the Rockies unless in connection with some new frontal system.

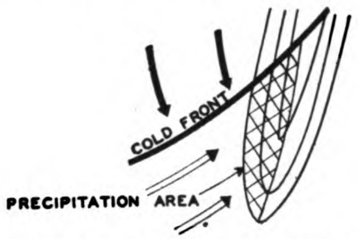


FIGURE 165.—Precipitation in mountains ahead of a cold front.

(2) A front that is parallel to a mountain range will cause precipitation all along a mountain range. A front that is perpendicular to a mountain range will cause a small precipitation area at the heart of the range.

(3) The trapping of cold air by a mountain range causes continual lifting of air over a semipermanent warm front and produces continued heavy precipitation as shown in figure 166.

(4) The top of the mountain ranges will normally be the last place that the warm front will appear. The warm front will usually go on over the top of the cold air to the lee of the mountain, causing continued

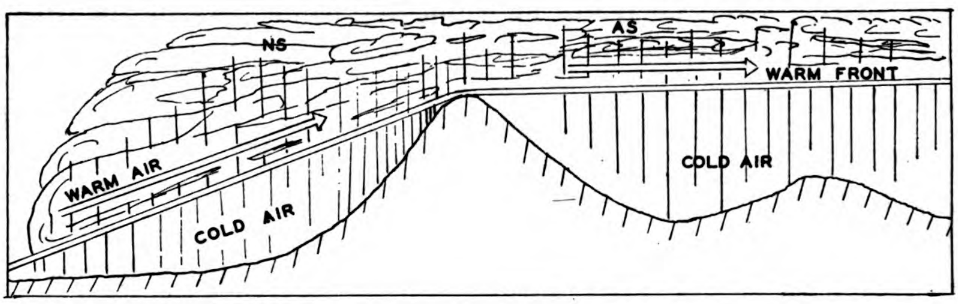


FIGURE 166.—Warm air lifted by trapped cold air.

precipitation. An exceptionally strong pressure gradient may bring the warm front to the ground again but it usually remains aloft. A cold front or cold front type occlusion will dig out the trapped cold air and stop precipitation.

(5) The retardation of a warm front at the southern tip of a high mountain range may form a secondary low center by causing a wave in the warm front. This sometimes occurs at the southern edge of the Rocky Mountains.

(6) Frontogenesis frequently occurs and new waves are often formed along the discontinuity surface between foehn winds and colder air.

This occurs to the lee of the Rocky Mountains where the foehn wind is Pp air and the cold air ahead of it is Pc or RPp. Waves developed in this manner have a frequency of about 12 hours, and they follow each other from the east flank of the Rocky Mountains across the United States. Frequently the air masses associated with these waves are so dry that the lift required for the formation of clouds and precipitation is more than that given by the frontal system. The result may be a fairly well defined cyclone with clear skies. These systems often cause no precipitation until they encounter Tg air. Thick Pc air just east of the Rockies frequently causes blizzard conditions in winter due to the overrunning Pp or Tp.

e. Valley and mountain breezes.—(1) Valley breezes occur during the day when the cold air in the valley replaces the warm air that rises from the mountainside. The valley breeze attains its maximum development in summer during the hottest part of the day. When the valley air is moist, it produces cumulus clouds along the flanks of the mountains.

(2) The mountain breeze is the reverse of the valley breeze. It occurs at night when the air along the mountainside becomes colder than that in the valley and slides down the mountain. This wind may attain relatively high velocities in steep canyons. The effect of the valley and mountain breeze varies with the seasons and the insolational effects at different latitudes.

131. Local showers.—*a*. The development of local showers in flat areas requires superadiabatic lapse rates, at least in the lower levels. In mountainous regions, steep lapse rates are not required because of the development of the valley breeze with resulting cumulus clouds and sometimes showers. In the later summer and fall, the westward extension of the Bermuda High may cause showers on the eastern slopes of the southern Rockies and Sierra Nevada Mountains.

b. Showers that develop on the windward slopes cause a down draft of cold air which opposes the rising warm air, thereby hindering the persistence of the shower with the tendency to develop only fair weather cumulus. However, when the cumulus clouds and showers are blown over the mountains, the cold air rushes down the lee side unopposed and displaces upward the warm air in its path and maintains cumulus clouds and showers. Normally in New Mexico and Arizona, the bases of these clouds are above the mountaintops and, when a shower cloud develops, it moves across the mountain with the prevailing wind.

c. High-wind velocities cause mixing and are detrimental to the formation of cumulus clouds and showers.

132. Flow over a mountain ridge.—*a.* With fairly high wind velocities, the flow pattern developed in mountainous regions acquires some unusual features. In some cases the wind may be quite helpful to the pilot and in others it may be a distinct hazard.

b. The flow over a mountain ridge, more or less uniform in height, is fairly uniform as the air moves upward. Velocities near the base are somewhat cut down, but with an increase in altitude the wind picks up in strength until it may assume quite high values over the top. This is especially true if the air is stable and is being forced over by a high pressure gradient.

c. The air stream lines begin to rise 30 or more miles to the windward of the ridge, the rate of ascent increasing as they approach the

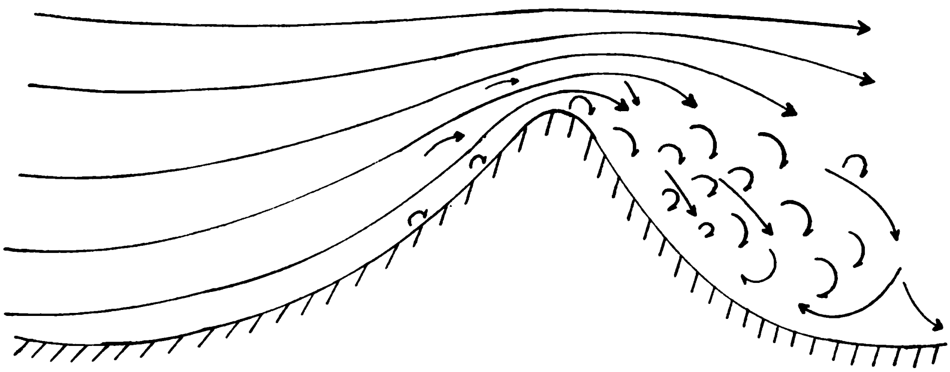


FIGURE 167.—Flow over a mountain ridge.

ridge. Hence, a 10,000-foot mountain range may cause clouds and precipitation up to 30 or more miles to its windward.

d. The stream lines over the top of a mountain ridge continue to rise until about a mile beyond the top of the ridge and roughly 2,000 feet above it, with a 30-mile-per-hour wind. As they come down the lee side, the flow becomes turbulent from ground levels to about half the height of the ridge and over an area extending several miles to the lee of the ridge. The general motion in the turbulent zone is roughly downward parallel to the surface of the ground, being more vertical the steeper the slope. Backset eddies may be formed. In strong winds, this flow is sufficient to cause some airplanes to sink when held at maximum climb.

e. The rising currents to the windward of the mountain ridge are used advantageously by soaring pilots. They may also be used by heavier aircraft to accomplish a rapid gain of elevation.

f. Clouds formed on the windward side are rapidly dissipated to the lee of the ridge due to the adiabatic heating of the foehn wind. When precipitation occurs and the clouds persist to the lee of the

mountaintop, the ceiling will be higher on that side, the differential being directly proportional to the amount of precipitation. Clouds formed on successively parallel ridges will have their bases at successively higher levels depending upon the amount of precipitation that occurs over each ridge.

133. Flow through mountain passes and valleys.—*a*. When air flows rapidly through a mountain pass, there is a turbulent zone near the ground on all sides of the pass. Bumps along the mountain sides and the edges of the pass are particularly rough if these edges are not smooth. They always cause discomfort to passengers and may in extreme cases cause structural damage. The flow directly through the center of even a rather restricted pass contains little turbulence and a flight may be made in this region without hazard. However, wind velocities may exceed 150 miles per hour and may considerably retard progress against the wind. A notable example of such flow occurs in the Columbia River gorge, a sea-level passage through the 5,000-foot Cascade Mountains, where stable air from the Great Basin HIGHS is forced through the gorge. At Crown Point near the western end of the gorge, wind velocities in excess of 40 miles per hour have been recorded for days at a time, with maximum winds more than 120 miles per hour. During such periods, wind velocities of 6 to 8 miles per hour have been reported at Portland, Oregon, 24 miles to the west. Airplanes flying at 145 miles per hour have been unable to get through the San Gorgonio Pass, to the east of March Field, due to strong head winds.

b. At the edges of the Los Angeles Basin, strong winds through Cajon Pass are confined, deflected, and strengthened by eastern winds through San Gorgonio Pass to produce what is known locally as the "Santa Ana." These strong winds strike the valley floor some 10 to 15 miles to the southeast of Cajon Pass, pick up dust and continue on over San Pedro Harbor and Catalina Island. Wind velocities up to 50 miles per hour have been reported in the harbor while surrounding winds in the basin were light. Some damage to fruit and shipping has resulted from this local wind.

c. In the Hawaiian Islands, on the Island of Oahu, the trade winds strike against the almost vertical flanks of the Koolau Mountains, rise very rapidly, and produce almost daily cloudiness and showers. They descend more gradually down the valleys on the lee side of the range. The crest of this ridge is quite sharp and severe turbulence is usually encountered while crossing it. Due to the down draft and the upward slope of the valleys from the southern side, aircraft crossing this ridge against the wind must attain a safe altitude before at-

tempting to negotiate the pass or further forward flight may become impossible without enough room or altitude to turn around. These principles may be applied to any flight up a narrow valley with a fairly steep slope of the valley floor, which may appear relatively flat to the pilot. Many airplanes do not have an angle of climb steeper than the slope of an average hill.

134. Flow up long gradual slopes.—*a.* As air moves up a long slope, its saturation level above the ground is continually being reduced. This leads to the very simple, yet most important, conclusion that as higher ground is reached, reduction of ceilings and visibilities may be expected. The result is that contact flying, especially in rough terrain with a gradual upslope, may become quite hazardous, particularly at night. It is often advisable to attain and maintain a safe altitude, by instruments if necessary, or seek a better route. The name "upslope fog" has been given to such cases where the ceiling comes down to the ground.

b. The gradual slope in west Texas and the southern Rocky Mountain area lifts summer Tg air to the level where its instability may be released causing showers and thunderstorms. This type of activity also prevails along the Appalachian Mountains, particularly in summer.

135. The Great Lakes.—These large bodies of water profoundly affect the weather in surrounding areas. In winter, they cause cold Pc masses to become unstable with resultant precipitation, icing conditions, fog, and low ceilings. In summer, they stabilize warmer air and provide a moisture source necessary for fog. When flying near the Great Lakes, consideration should be given as to whether the general flow is onshore or offshore. Onshore winds, particularly in winter, frequently cause hazardous flying weather.

136. Ocean shore lines.—The oceans are the greatest source of moisture and onshore winds are frequently at or near saturation. The most persistent and frequent fogs and low stratus are associated with onshore winds. Wind direction along shore lines and time of day should be continually kept in mind in relation to the existence or possibility of the formation of fog and low stratus. Fogs form most frequently at night.

SECTION XVI

CLIMATOLOGY

137. General.—*a.* Climate is the summation and average of the daily weather. Climatic records have been obtained in the past by summing up and taking the average of temperature, wind direction and velocity, rain, maximum temperature, minimum temperature, sunshine hours, and certain other factors.

b. Newer methods of attack include the determination of weather as a result of the action of air masses and fronts over the specified region during a given forecast interval. Seasonal forecasting may be performed on the basis of knowledge of the physical processes involved.

138. Detailed Methods.—*a.* Consider the various air masses that occupy a given area, together with the frontal activity that may occur.

b. Classify the types of fronts as Pc–Tg, Pp–Tg, Pp–Pc, as well as whether these are cold fronts, warm fronts, or the proportion of each.

c. Indicate whether the fronts are active or passive.

d. Determine thunderstorm activity and whether it is in connection with cold fronts, warm fronts, or air masses.

e. Consider the effects of terrain.

f. Determine the method of oscillation of the polar front as to both its seasonal and yearly variation.

Example:

Air mass:

	Days in winter
$_2$PP$_3$	53
TG$_2$	37

These data indicate that the station is a little north of the mean position of the polar front. Refinements of this method give results showing what factors control the climate of a particular area. Hence a knowledge of the cause of climate will aid in climatic forecasting.

139. Ocean effects.—Surface temperatures of the oceans adjacent to land masses control the physical properties of the maritime air that moves over the land. Since maritime air masses are involved in such a large portion of United States weather, it is essential that the forecaster familiarize himself with the surface temperatures of adjacent oceans. Ocean currents do not have fixed trajectories and even though the variations in ocean temperature over a given area are not usually large, the variations that do occur may have a great effect upon the properties of the air masses that pass over. It seems probable that accurate knowledge of ocean currents and existing ocean temperatures would aid greatly in seasonal and annual forecasting.

140. Climate.—*a. In the tropics.*—Tropical regions are rarely vis-

ited by fronts as we know them in the middle latitudes. Wind direction is more or less constant. Forecasts of seasonal climate from averages may be reasonably accurate since usually only a single type of air mass is present.

b. *Along Pacific coast.*—(1) The summers are very similar. The difference in the amount of fog is usually the only considerable change.

(2) The winters vary considerably due to the various controlling factors. This region is frequently under the influence of offshore currents from the Great Basin anticyclone and during such periods there is no rain and the weather is warm. The problem is to determine the frequency of this type of air and forecast accordingly. Rain comes chiefly from TP and PP air. The amount of rain is a function of the stability of these air masses and the number of fronts that cross the region in a given time. PP air is the only type of air that will produce large amounts of snow on the mountains. Icing conditions frequently exist. TP air occurs infrequently and irregularly. The stability of the TP causes a more uniform and widespread distribution of rain when this air mass does arrive. Sometimes PC air invades the region and these invasions account for the only severe cold spells. When ocean temperatures are less than usual, TP air will be colder and more stable in the lower levels. When the ocean is warmer than usual, TP air will be more unstable and produce more clouds and precipitation.

c. *In the Middle West.*—(1) Summers are characterized by high temperatures, scattered showers, and thunderstorms. TG air occupies the region most of the time, PC and PP air occurring chiefly in the northern portion. Ceilings are usually unlimited and visibilities more than 15 miles except where they are restricted by smoke during the night and early morning near cities. Early morning ground fogs occur frequently near the Great Lakes. The highest temperatures exist when TC air enters from the southwest. Periods of a week or more with temperatures above 100° are not unusual.

(2) In winter, PC air causes extreme cold and occasional snow flurries, especially south of the Great Lakes. Blizzards are caused by TP, PP, or TG overrunning fast moving PC. PP air brings a cool respite from the cold PC. TG provides infrequent warm spells that are usually initiated and ended by widespread precipitation, low ceilings and visibilities. Winters vary considerably from year to year with the greatest variation occurring east of the Amarillo-Wichita-St. Louis-Detroit line. The polar front remains almost continually south of the area. Icing is common.

d. *In the Gulf States.*—(1) In summer, the States bordering the Gulf

of Mexico are almost continually occupied by TG air. Scattered showers and thunderstorms in the late afternoon with low stratus ceilings from 800 to 1,500 feet at night are the rule. Relative humidities are high and day temperatures usually reach the high nineties in areas more than about 75 miles from the coast line. Occasionally Tc brings a hot spell to east Texas and Pc sometimes reaches as far south as the eastern Gulf States.

(2) The polar front oscillates across this area in winter. It is therefore a region of frontogenesis with extremely variable weather during the winter season. The deceleration of polar fronts, stationary fronts and the formation of RPC, RPP and TG warm fronts combine to produce widespread precipitation and fog areas. Ceilings and visibilities are extremely low during these periods. Thunderstorms along the fronts add to the aviation hazard. Icing situations are unusual although they do exist.

e. Along the central and north Atlantic coast.—(1) The polar front moves back and forth across this region in summer. When it is to the north, TG air occupies the area and when it is to the south, Pc or PP air bring cooler, clearer weather. The change occurs almost weekly with attendant showers and thunderstorms. Cyclonic systems off the coast sometimes bring in cool PA air with attendant onshore fog and low stratus.

(2) Pc is the chief air mass in winter. Temperatures are usually higher than in the Middle West because of the föehn effect from the Appalachian and New England Mountains. These mountains also protect the Coastal States from the snow flurries caused by the Great Lakes. Ceilings and visibilities in Pc far from frontal zones are usually ample for safe aircraft operation although the temperatures are low. The most severe weather occurs when cyclonic systems from the west or southwest cross the area. The intensity of these waves usually increases as they progress from the Gulf or Rocky Mountain area to well out in the Atlantic Ocean. Widespread precipitation, clouds, fog, and low stratus areas occur. Wind velocities become unusually high. Ceilings and visibilities come down and icing conditions are frequent, especially in the mountains. Passes are closed and aircraft are allowed to operate only through the use of instrument flying. TG air rarely appears at the surface unless associated with a frontal system. PP air occasionally brings periods of clear weather with moderate temperatures.

APPENDIXES

APPENDIX I

LIST OF SUPPLEMENTARY TEXTS AND SUBJECTS

OCAC Circular 105–5 (Circular 105–5):
- Subjects:
  - Weather service; construction of weather maps.
  - Charts and diagrams.
  - International symbols.

Instructions for Airway Meteorological Service, Circular N, Aerological Division, Fourth Edition 1939 (Circular "N"):
- Subjects:
  - Winds aloft.
  - Explanation of symbol weather reports.
  - Sample weather sequences.

Air Corps Radio Facility Chart (ACRFC):
- Subjects:
  - Stations and station designators.
  - Weather broadcast schedules.

APPENDIX II

ISOBARIC ANALYSIS

1. Errors.—The purpose of isobaric analysis is to draw representative isobars, or the isobars which would result if the barometric observations were perfect; if there were no local disturbances or local errors in reduction to the standard level (sea level); and if the observations were strictly synchronous. The errors which occur in weather reports are personal errors of observations, errors of reduction to sea level, errors caused by the observation being made too early or too late, errors of coding, transmission, decoding, and plotting, and errors caused by the code itself. In drawing isobars one should try to render these errors ineffective. Regardless of the nature of the errors in the reported pressure, the error in placing the isobars will be large when the pressure distribution is "flat" but small when the pressure gradient is "steep."

a. Personal errors, or errors of accident, are difficult to detect when they are small. Such errors should not show any systematic arrangement on the chart, and the isobars should therefore be smoothed. Since simple isobars are much more probable than complicated isobars, one should always try to smooth the irregularities which do not show any systematic arrangement. If there is reason to suspect that the pressure report from a station is wrong, one should compare the pressure variation between the present and the preceding observation with the same variation for neighboring stations, and also see that the reported tendencies make it plausible that such a variation has taken place. Large errors can easily be detected in this way. This particularly applies to land stations.

b. Errors of reduction to sea level only affect stations whose altitude is considerable. The errors are large when the temperature distribution is abnormal. In drawing isobars, one should place more weight on the reports from low stations than high stations. Accurate reports usually cannot be expected from stations whose altitude is over 1,500 feet.

c. Time errors.—If the observations are not made exactly at the standard hour of observation, there will be an error in the reported pressure referred to the standard hour of observation. If the barometric tendency is T and the error in time is t minutes, the error in

the reported barometric pressure is $\frac{Tt}{180}$. Thus, if t is 15 minutes, the error will be $T/12$. The error is therefore directly proportional to the barometric tendency, and it will usually be of importance only when the barometric tendency is large. There can be little doubt that time errors of 20 minutes occur frequently. The reported pressures would therefore often be inaccurate when the barometric tendency is 4 millibars or more. In such cases there is no reason to believe that small irregularities in the pressure distribution are real unless they show some systematic arrangement. There is therefore, theoretically more reason for smoothing the isobars in areas where the tendencies are large than in areas where they are small.

d. Errors of coding and decoding depend on the nature of the code. In the International Code such errors should not occur, because the barometer is read and the observation written in tenths of millibars and the tendencies are read and written in fifths. Errors of transmission may occur in the International Code; however, experience from Europe shows that such errors are rather rare. A special type of error occurs in the ship reports when an error occurs in the position of the ship. Errors of transmission or coding will usually be 1° or 10° longitude or 1° or 10° latitude. Such errors can easily be detected by tracing the track of the ship. Plotting errors in the position of the ship are usually either 1° or 5° longitude or latitude. Such errors can be checked directly.

2. Principles of drawing isobars.—In trying to neutralize the errors mentioned in paragraph 1, it is useful to bear in mind the following principles:

a. In representing a large scale movement of the atmosphere, simple isobars are much more probable than complicated isobars. This principle does not result from any theoretical considerations; it is merely a fact of experience. It is true that the isobars of the turbulent air motion would possibly be very complicated, but in all air currents which are of such magnitude and duration that the Coriolis force has time to regulate the movement of the air, there is a decided tendency to simplify the isobars. This is most pronounced in stable and homogeneous air; the stronger the air current the smoother the isobars. However, in flat pressure situations, especially in summer in an unstable mass, complicated isobars may occur as a phenomenon. In such cases one should always draw individual isobars for each millibar or isobars for every 0.5 millibar. If the isobars thus drawn show either a systematic arrangement of the irregularities, a definite center of low, or a definite trough, the irregularities should be regarded

as real. In warm summer situations, such pressure formations often favor the formation of thundershowers, and it is therefore very important to distinguish real irregularities from those resulting from errors. Irregularities of this kind usually occur in stagnant areas where a front, notably a cold front, has dissolved or is dissolving.

b. The isobars should have such direction and such mutual distance that they approximately agree with the Buys-Ballot Law. Let V denote the magnitude of the geostrophic wind velocity, Δp the pressure difference between two isobars, Δs the distance between two isobars, $\Delta p/\Delta s$ the pressure gradient, ρ density, ω angular velocity of the earth's rotation, and ϕ latitude. We may then write:

$$V = \frac{\Delta p}{\Delta s \rho 2\omega \sin \phi}$$

Since the horizontal variation in ρ is very small, we may regard $\rho\, 2\omega \sin \phi$ as a constant for each latitude. The geostrophic wind is therefore directly proportional to $\Delta p/\Delta s$. This quantity is easily evaluated from the isobars. Drawing isobars for every 3 millibars, we see that V is inversely proportional to the distance between the isobars.

If the wind were strictly geostrophic, the above equation would hold for the true wind. But usually the observed wind is influenced by friction along the surface of the earth, and the observed representative wind velocity is therefore considerably smaller than the geostrophic wind.

Statistical investigations show that the observed wind velocity is roughly 70 percent of the geostrophic at sea and 40 percent over land.

The relation between wind and isobars is particularly useful over oceans where the problem is to draw the isobars by means of a few scattered ship reports.

The direction of the geostrophic wind coincides with the isobars in such a way that the wind blows along the isobars with low pressure to its left. However, friction and acceleration cause the true wind to be deflected from the isobars toward lower pressure. The angle between the isobar and the wind direction is usually 20° to 30°.

The relation between the direction and the force of the observed wind, and the direction of the isobars and the distance between neighboring isobars are one of the most valuable means for drawing correct isobars in regions where reports are scanty. It is therefore of utmost importance that the wind observations at such stations are representative. The practical methods of placing the isobars will be described later.

c. The isobars in the vicinity of fronts should be drawn in accordance with the formula for the velocity of the front.

The formula for the velocity of a front is—

$$C_f = \frac{\frac{\theta p_1}{\theta t} - \frac{\theta p_2}{\theta t}}{\frac{\theta p_1}{\theta x} - \frac{\theta p_2}{\theta x}}$$

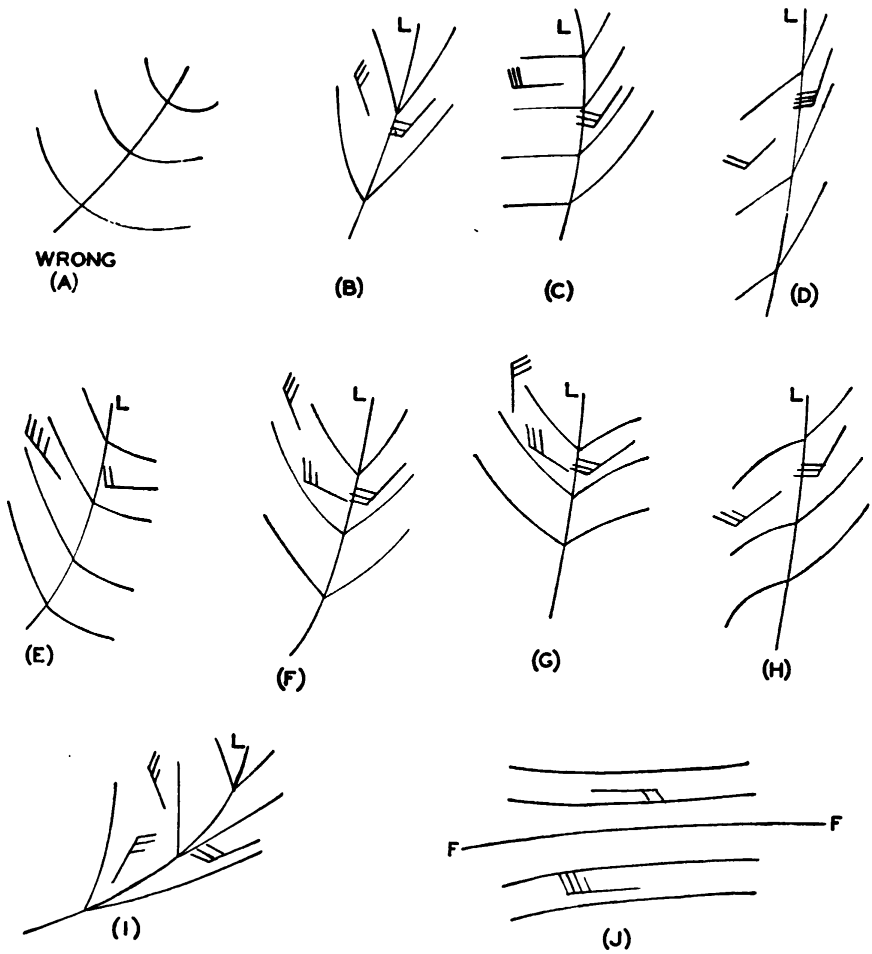


FIGURE 1

The denominator is always positive and different from zero. From this it follows that there must be an angle in the isobars at the front. This angle is such that it is less than 180° when reckoned through low pressure.

Isobars in the vicinity of fronts should never be drawn as smooth curves because then $\frac{\theta p_1}{\theta x} - \frac{\theta p_2}{\theta x} = o$ which is not possible.

Figure 1 shows some examples of types of isobars in the vicinity of fronts. Figure 1 (*a*) is wrong because there is no angle in the isobars at the front. Figure 1 (*b*) shows a case when the wind velocity is equal at both sides of the front. The distances between the isobars should then be the same in advance and in the rear of the front. Figure 1 (*c*) and (*d*) show cases with less wind in the rear of the front than in advance of it. Figure 1 (*e*) shows a case with moderate wind in advance and strong wind in the rear. Figures 1 (*f*), (*g*), (*h*), and (*i*) show various cases of curved isobars.

3. Geostrophic wind scale.—In order to demonstrate more accurately the relation between wind and isobars, the construction and the uses of geostrophic wind scale are here described.

The geostrophic wind is given by—

$$V = \frac{\Delta p}{\Delta s \rho \times 2\omega \sin \phi}$$

In rational units V is given in m/sec., p in centibars, Δs in meters, and ρ in ton/m^3.

The equation of condition gives $p = \rho RT$ where $R = 287$. Choosing $T = 300$ absolute as a mean value for temperature, and $p = 100$ centibars for pressure, we obtain:

TABLE I.—*Latitude 45° chart scale 1/10,000,000*

Lower limit of Beaufort No.	Velocity mps V	Distance on earth in meters between isobars 0.3 mb. apart Δs	Distance on chart in millimeters between isobars 3 mb. apart	6-hour displacement in meters on earth Δs	6-hour displacement in millimeters on chart
2	1.79	1,400,000	140.0	38,700	3.9
3	3.58	701,000	70.1	77,400	7.7
4	5.81	432,000	43.2	125,800	12.6
5	8.49	296,000	29.6	183,000	18.3
6	11.18	224,200	22.4	241,800	24.2
7	14.31	175,200	17.5	308,500	30.8
8	17.43	144,000	14.4	376,000	37.6
9	21.01	119,600	11.9	455,000	45.5
10	24.59	103,100	10.3	531,000	53.1
11	28.61	87,600	8.7	620,000	62.0
12	33.53	74,900	7.5	724,000	72.4

213541°—40——17

TABLE II.—*Latitude 30° chart scale 1/10,000,000*

Lower limit of Beaufort No.	Velocity mps V	Distance on earth in meters between isobars 0.3 mb. apart Δs	Distance on chart in millimeters between isobars 3 mb. apart	6-hour displacement in meters on earth Δs	6-hour displacement in millimeters on chart
2	1.79	1,982,000	198.2	38,700	3.9
3	3.58	992,000	99.2	77,400	7.7
4	5.81	612,500	61.2	125,800	12.6
5	8.49	419,000	41.9	183,000	18.3
6	11.18	318,000	31.8	241,800	24.2
7	14.31	248,000	24.8	308,500	30.8
8	17.43	204,000	20.4	376,000	37.6
9	21.01	169,000	16.9	455,000	45.5
10	24.59	145,000	14.5	531,000	53.1
11	28.61	124,000	12.4	620,000	62.0
12	33.53	105,900	10.6	724,000	72.4

$$\Delta s=\frac{.3\times 3\times 287\times 6\times 60\times 60}{V\times 3.1416\times \sin 30^\circ}=\frac{.9\times 287\times 21600}{V\times 3.1416\times .5}=\frac{355\times 10^4}{V}$$

$$\Delta s=\frac{.3\times 3\times 287\times 6\times 60\times 60}{V\times 3.1416\times \sin 45^\circ}=\frac{.9\times 287\times 21600}{V\times 3.1416\times 707}=\frac{251\times 10^4}{V}$$

$$\Delta S=V\times 60\times 60\times 6=V\times 216{,}000$$

$$\rho=\frac{100}{287\times 300}$$

When isobars are drawn for each 3 millibars, we substitute—

$$p=3 \text{ millibar}=0.3 \text{ centibar.}$$

Choosing Δs as unknown, and substituting in the above formula for V, we obtain—

$$\Delta s=\frac{.3\times 3\times 287\times 6\times 60\times 60}{V\times \pi\times \sin \phi}$$

From this formula we compute a table of distances (Δs) between neighboring isobars which correspond to the various wind forces in the Beaufort Scale. The distances thus computed naturally must be transferred to the scale of the chart and the distances would vary with latitude in the proportion of $1/\sin \phi$. Table I gives the distances between neighboring 3 millibar isobars for latitude 45° and chart scale 1/10,000,000. Table II gives the same for latitude 30°. In order to find the corresponding distances for latitude 60°, it suffices to subtract 20 percent from the distances given for latitude 45°. In tables I and II are also given the distance the particle would travel in 6 hours if the wind velocity were equal to the geostrophic wind. It is convenient to transfer the above figures to a scale as shown in figure 2 ① for latitude 45° and in figure 2 ② for latitude 30°. This scale can be used for various purposes.

a. When the isobars are drawn, place the base line (fig. 2 ① or ②) on the isobar. If the neighboring isobar falls between the Nos. 8 and 9, the geostrophic wind would be 8 on the Beaufort Scale. The wind above the friction level (roughly 1,200 feet) would then be approximately 8 on the Beaufort Scale. The representative wind at station

level would be less than the geostrophic value; over sea roughly 70 percent and over land 40 percent of the geostrophic value.

b. When a representative station reports barometer 1018.5 and wind velocity 6, the station would be situated halfway between the 1017 and the 1020 isobars. The distance between these isobars would be 70 percent of the distance between the base line and figure 6 on the scale when the station is an ocean station, but only 40 percent if it is a land station.

If the barometer were observed 1019, the 1020 isobar would be close to the station and 1017 isobar farther away. Thus the geostrophic wind scale can be used for spacing the isobars in the vicinity of

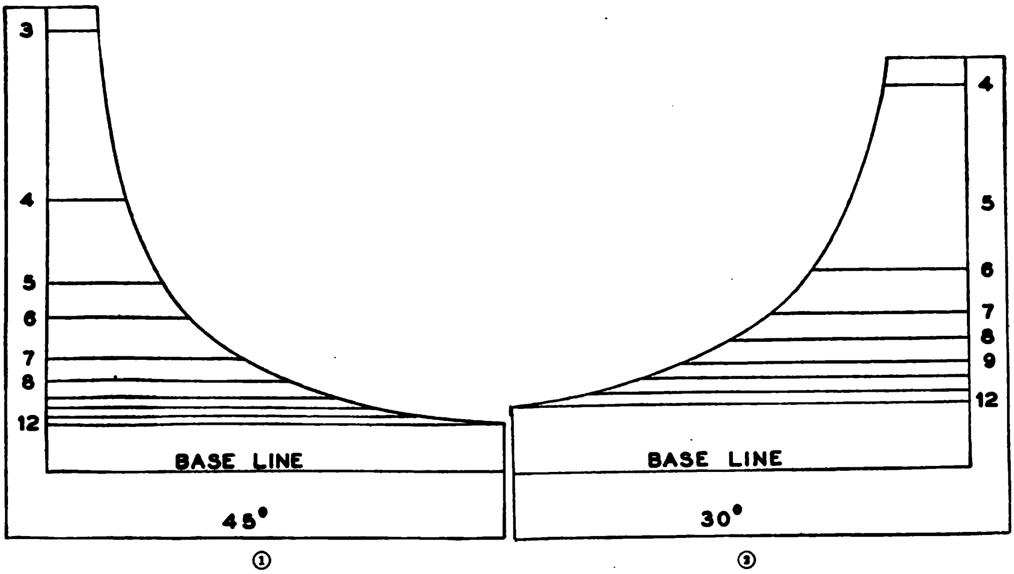


FIGURE 2.—Geostrophic wind scale for chart. Scale 1/10,000,000

reported stations. This spacing is of crucial significance over oceans where the analysis must be based on only a few scattered reports.

The isobars thus drawn should have such a direction that the wind blows 20° to 30° inward toward lower pressure.

c. If the distance between neighboring isobars corresponds to 8, then the distance that the particle would travel in 6 hours would be equal to the line through 8 and parallel to the base line, provided that the wind velocity is geostrophic. Since the wind above the friction layer is approximately geostrophic, the above scale can be used for exterpolating the movement of fronts and air masses.

The rules for spacing isobars are based on the assumption that the wind velocity is representative. This is usually the case with the wind velocities at sea and also at well-exposed stations over flat country when the velocity itself is strong. Slight wind velocities are usually not so representative that the scale can be used with advantage.

Apart from the above principles, one should always try to obtain the most probable distribution of isobars by considering the previous charts and the neighboring pressure systems. The problem will often be to obtain an even and logical distribution of the isobars where there are no fronts, and to bring out typical frontal characteristics in the frontal zones. The way this is done is illustrated in the examples in paragraph 4.

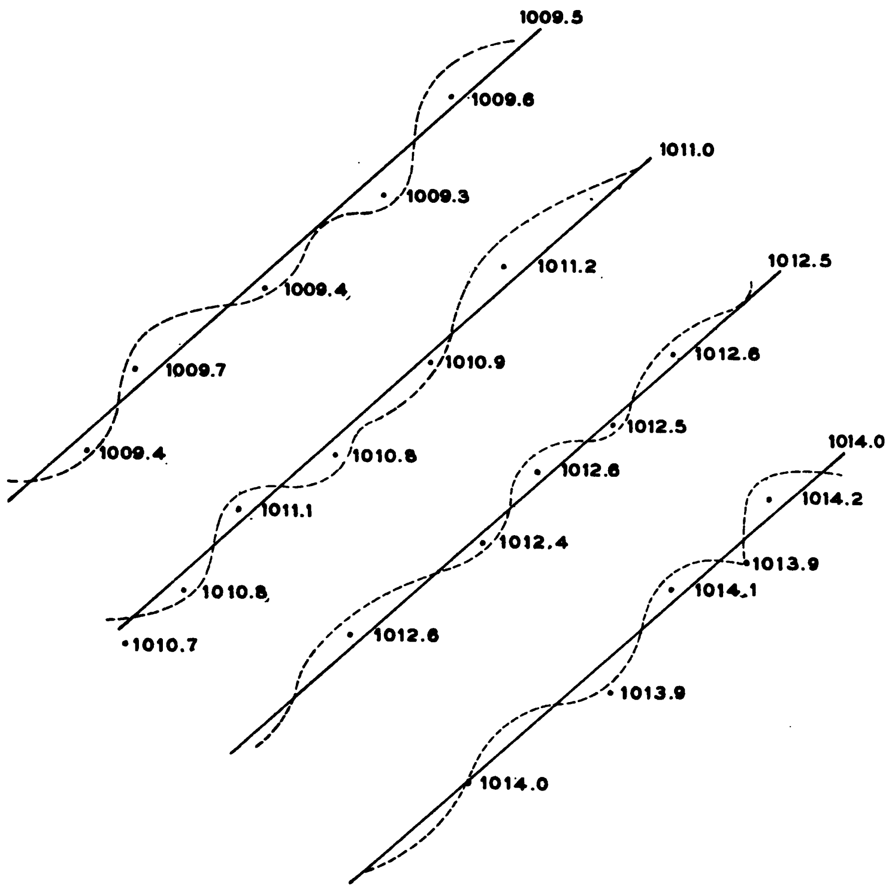


FIGURE 3.—Irregular isobars which should be smoothed because the irregularities do not show any systematic arrangement.

4. Examples of drawing isobars.—Figure 3 shows a case of irregular isobars where there is no systematic arrangement. The broken lines are drawn according to the reports, and the full lines are the isobars which logically result by smoothing out the irregularities. The justification for smoothing out the irregularities is that each irregularity seems to depend on one station only.

Figure 4 shows a case of real irregularity. In drawing only every three millibar isobars, the irregularity is not apparent. In drawing isobars for every 0.5 millibar, we see that several stations agree

mutually. The irregularity should thus be regarded as real. Whether or not a front is associated with it should be decided by studying the

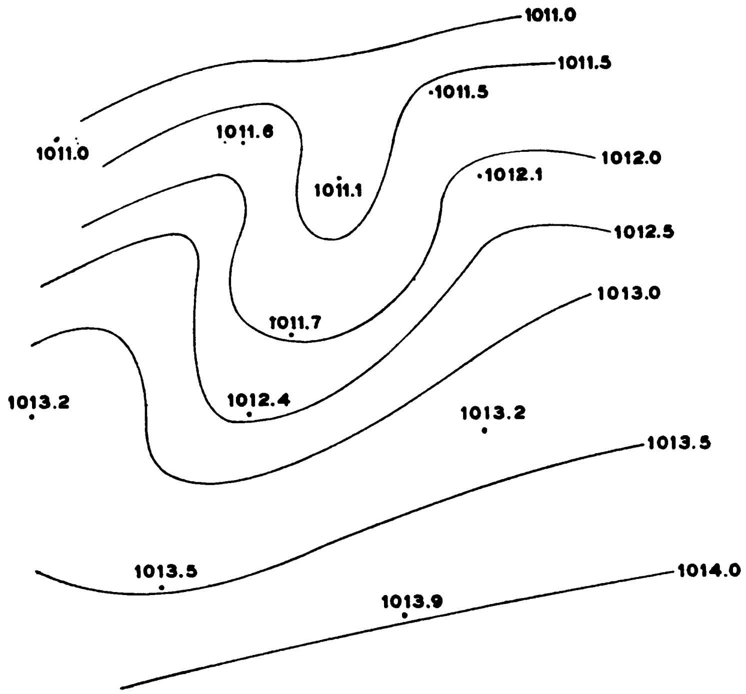


FIGURE 4.—Showing irregular isobars in a flat area. The irregularities should (apart from minor deviations) be regarded as real ones because the stations agree mutually. In such cases, draw in between isobars.

front characteristics and the air mass properties, and also by applying the principle of historical sequence of the conditions for frontogenesis.

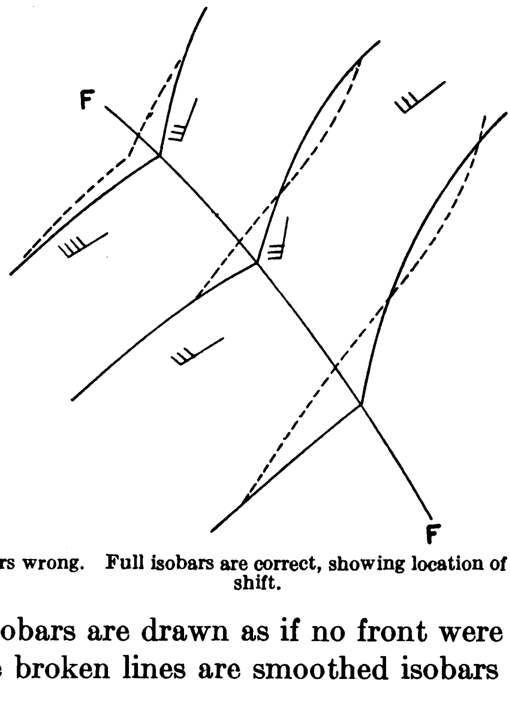


FIGURE 5.—Dashed isobars wrong. Full isobars are correct, showing location of front and explaining wind shift.

In figure 4 the isobars are drawn as if no front were present.

In figure 5 the broken lines are smoothed isobars and the full lines

isobars drawn according to pressure and wind observations with smoothing only for accidental irregularities. It is seen that along the line *FF* there is an irregularity in the isobars which is systematically arranged. This should not be smoothed. In fact, such an irregularity however slight is often an indication of a front. In such cases one should carefully examine the conditions along the line *FF*.

Figure 6 shows an example of two ship reports with a warm front between the ships. The problem is to draw the most logical isobars. Use the wind velocity to space the isobars correctly in the vicinity of both stations. Allow the winds to blow slightly toward low pressure. Since the warm sector air is homogeneous, the isobars

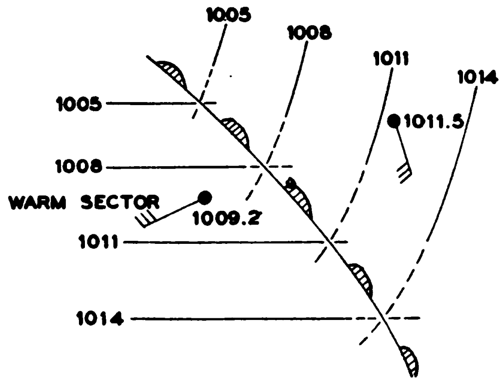


FIGURE 6.—Showing extrapolation of isobars to determine location of a warm front by use of the geostrophic wind scale.

should be drawn to intersect the warm sector isobars in such a way that the front (through the points of intersection) gets a logical trend without undue variations in direction. In this way it is frequently possible to locate the front with great accuracy.

Figure 7 shows some instructive cases. In (*a*) to (*d*) the conditions are exactly the same except that the pressure of the northernmost station increases by 2 units for each successive figure. In (*a*) the front runs approximately from northwest to southeast and very close to the northernmost station. As the pressure at this station increases, the front must be drawn closer to the southern stations and the front runs more east-west.

In (*e*) to (*h*) the pressure increases by 3 units for each picture at the northernmost station. It is seen how the front should be located in each particular case.

It is a rough rule to say the front should be drawn nearer the station which has the lowest pressure. This rule is not infallible. The exact position of the front will depend also on the wind direction. The student is recommended to work through a number of cases in

order to become familiar with the technique of locating fronts by means of the isobars. Over oceans this method is often the only one applicable and it is therefore of very great importance.

Isobars over a large area should be drawn in steps, beginning in the areas where the analysis is easiest. Figure 8 gives an example of how to proceed.

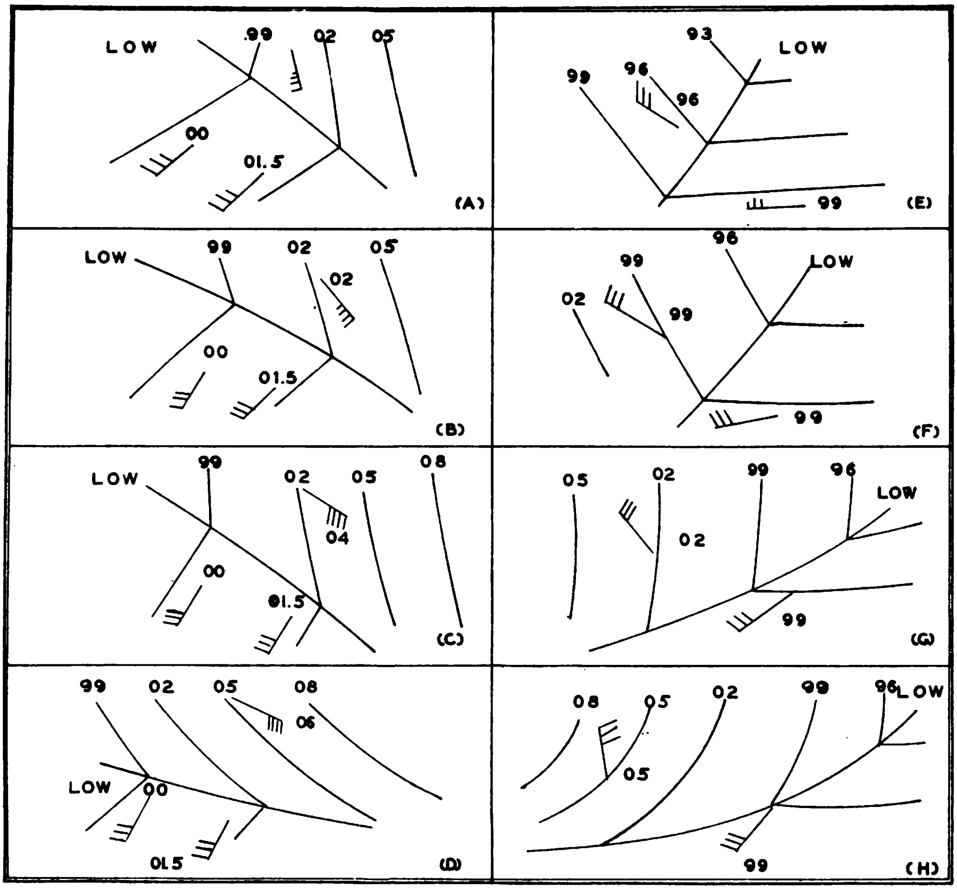


FIGURE 7.

We suppose that we know from a previous chart that a warm front is situated between the ships *A* and *B*. Use the geostrophic wind scale and space some isobars in the vincinity of *A*. Do the same around *B*. Since there obviously is a wedge of high pressure between *B* and *D*, one should not place too many isobars to the right of *B* because the pressure gradient might vary in this direction. To the left of *B* we may place quite a number of isobars because the isobars in the vicinity of *A* will check on the analysis. Next space in a few isobars around *D* and beware of the variation in pressure gradient between *B* and *D*. Since the velocity of *C* is slight, we should not

rely too much on the spacing obtained by the scale. The isobars thus drawn are shown as full lines in figure 8. Next try to combine the significant isobars in the various areas. The isobars thus obtained are shown as broken lines.

If any further observations are available, the pressure distribution in the other areas should be extrapolated from the previous chart and the whole analysis should agree historically with the previous charts or the previous charts should be corrected to agree with the present chart.

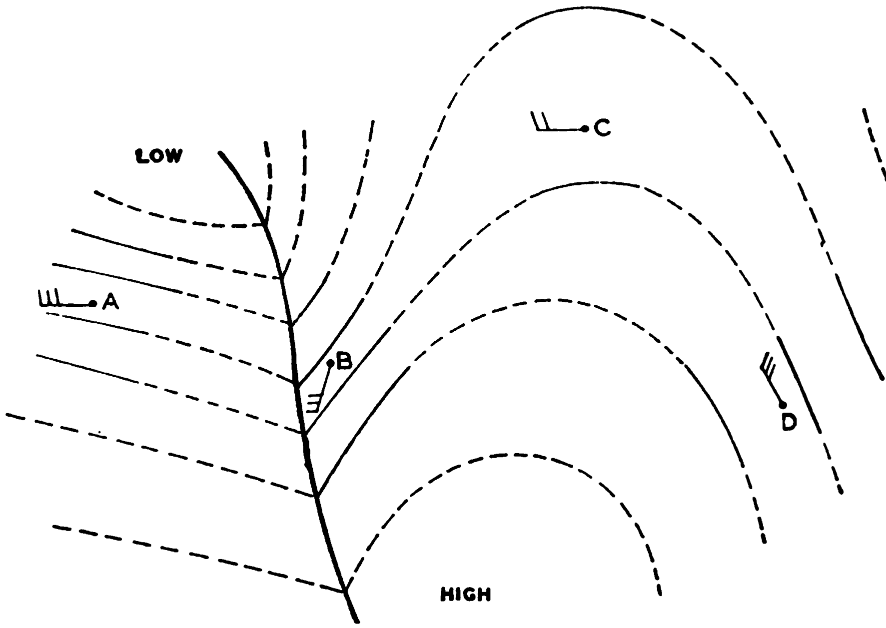


FIGURE 8.

Only by logical spacing of the isobars and by experimenting with various possible solutions and comparing with previous charts, taking into account the development which has taken place, will it be possible to obtain a satisfactory analysis.

5. Drawing of isallobars.—The isallobars should be drawn in such a way that accidental errors and irregularities are smoothed and on the same principles as when drawing isobars. Only irregularities which show a systematic arrangement should be regarded as real.

It follows from the formula for the velocity of a front (par. 2) that $\frac{\theta P_1}{\theta t}-\frac{\theta P_2}{\theta t}$ must be different from zero at all fronts which are not stationary, because otherwise the front velocity would be zero. Now, $\frac{\theta P_1}{\theta t}$ is the slope of the barogram in advance of the front and $\frac{\theta P_2}{\theta t}$ is the slope of the barogram in the rear of the front.

Figure 9 shows a barogram at three different stations, *A*, *B*, and *C*. We imagine that the stations *A*, *B*, and *C* are situated on a straight line perpendicular to the front shown in figure 10. The front is moving from *A* toward *C;* it appears from the barogram that the front passed the station *A* before 5 o'clock. The barometric tendency reported by *A* (that is, B_1) is approximately equal to the slope of the barogram at figure 7 (*h*).

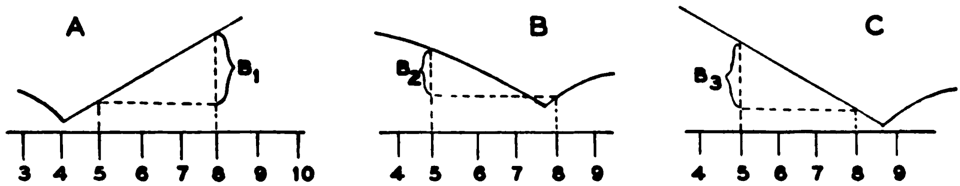


FIGURE 9.

The barometric tendency at *B* (B_2) is negative, but the slope of the barogram at 7 (*h*) is positive. Since the front has passed the station *B* with this tendency interval, it is obvious that the tendency reported immediately behind the front is not representative of the slope of the barogram and can therefore not be used in the formula for the velocity of the front.

Therefore, in advance of a front the barometric tendencies are representative, and the isallobars can be drawn according to the reported tendencies smoothed for accidental errors and irregularities.

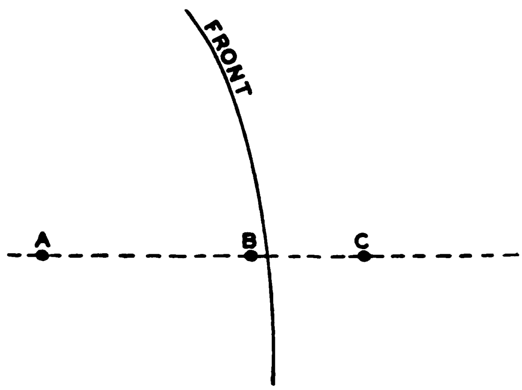


FIGURE 10.

The tendencies within the zone through which the front has passed during the last 3 hours are not representative.

The tendencies in the rear of this zone are usually representative. The isallobars in this area may be extrapolated through the zone through which the front has passed during the last 3 hours.

Figure 11 shows the position of a front at 0800 and the approximate position of the front at 0500. Draw the isallobars in advance of the front until they intersect with the front. Draw next the isallobars to the left of the line 0500 and extrapolate the isallobars toward the front. In this way we may observe a fairly accurate picture of the isallobars

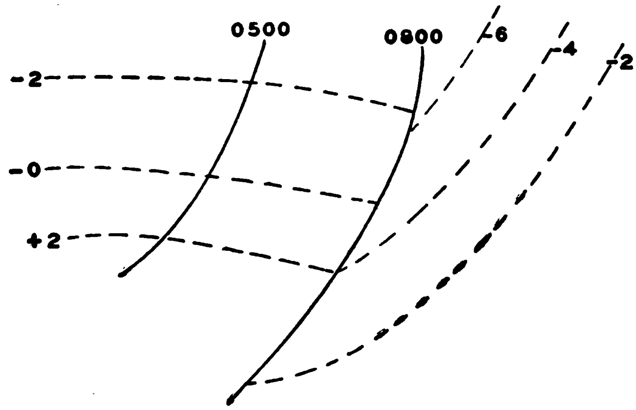


FIGURE 11.

in the vicinity of the front. The values for $\frac{\theta P_1}{\theta t} - \frac{\theta P_2}{\theta t}$ which should be substituted in the formula for the front velocity should be taken from the carefully drawn isallobars and not from the observations of the individual stations.

It is important to remember that the tendencies at stations where thunderstorms have occurred during the last 3 hours are not representative due to the irregular variation of barometric pressure during the passage of a thunderstorm.

APPENDIX III

FORECASTS

1. There are two types of forecasts issued by the Weather Bureau through the communication channels of the Civil Aeronautics Authority. Both forecasts are transmitted over the teletype every 6 hours for an 8-hour period. Examples of the two types are—

a. Airways forecasts (terminal).—1530–2330CS airways forecast 4/2 AG BH JX NO MS termls brkn to sctd dmshg cldns bcmg sctd to clr cig unl xcpt 35hnd lwr clds vsby 7 to 15 miles.

CS SH termls ovc with ocnl rain first two hours bcmg ocnly brkn to sctd after 1800CS stop cig 7 to 15 hnd lftng to 2 thsd or hir Savannah after 1900ES stop vsby 1 to 4 in rain othrw abv 6----------

JX terml brkn to ovc with ocnl shwr or thdrstm until 1900 es cig 15 hnd to 3 thsd lwr clds othrw unl lwrg to 6 to 12 hnd at times in shwrs stp vsby 1 to 4 in rain othrw abv 6----------

MM terml sctd to brkn ocnly ovc with ocnl spkl or lgt shwr cig 2 to 3 thsd in lwr clds othrw unl stop vsby abv 6 lwrg slightly in shwrs----

----

b. Airways regional forecast.—NOGW CSMM CSJA JXNA DBTM NOPS cold front Florence SC swwd to Gulf at 1230cs mvg abt 20mph sewd stp brkn to ovc with ocnl shwrs and thstms for abt 125 miles se of front and 50 miles nw of front xcpt contd spklg or mist wrn NC and sctd lgt shwrs srn FLA stp elsw over dist brkn to sctd bcmg clr to sctd Miss LA Ala wrn Ga stp cig grnly 2 to 4 thsd lwr clds lwrg to 6 to 15 hnd in precip area xcpt cnds ovr mtns stp vsby 1 to 4 in rain xcpt ocnly less than 1 mile nrn Fla othrw 7 to 15 miles end

----

2. The following type forecasts are issued by Air Corps weather stations:

a. Regional forecast.—Weather conditions over a geographical area or region during a given period of time.

b. Terminal forecast.—Forecast conditions for a particular airport during a period from 24 to 36 hours.

c. Route forecast.—Weather at geographical points along the route normally covering a 6-hour period.

d. Trip forecast.—The weather at various stations along a route that a pilot will encounter on a particular trip.

3. Elements of a forecast are given in the following order:

a. State of weather (overcast, broken, scattered, clear, or combinations thereof).

b. Precipitation (by type).

c. Ceiling (in thousands of feet if above 2,000 feet, in hundreds of feet if below 2,000 feet).

d. Visibility (in miles and fractions thereof).

e. Surface wind velocity (by direction and intensity).

f. Upper air wind velocities (by direction and intensity).

g. Best flying altitude (for route and trip forecasts only), that is, level of the most helping winds or least head winds.

4. Examples of forecasts are given below:

a. Regional synopsis.—0700CS 9/4/38. Weak front along Texarkana, Dallas, Brady, Del Rio line will produce broken to overcast cloudiness and scattered thunderstorms along frontal zone. Weak cold front south of Houston, Pass Cavallo Laredo line will continue to produce thunderstorms with decreasing intensity dissipating during the night.

b. Randolph Field terminal forecast.—0700CS 7/1/38 to 2400CS 7/2/38. Broken stratus clouds becoming stratocumulus by 0730CS. Broken clouds decreasing to scattered by 0830CS, decreasing during period 0830CS to 1300CS and increasing 1400CS to 1600CS. Cumulus clouds clearing after dark—low stratus clouds forming 0200CS Tuesday overcast 0230CS to 0830CS scattered 0830CS to 1900CS—becoming clear 1900CS for remainder of period.

Ceilings 1200 feet lifting to 1800 feet 0700CS to 0830CS unlimited thereafter with base of cumulus at 5000 feet after 1400CS—ceilings lowering after 0230CS Tuesday in stratus clouds to 1000 feet lifting 0730CS to 0830CS to 2000 feet and unlimited thereafter.

Visibility 12 to 15 miles.

Surface winds south to southeast 8 to 12 miles per hour increasing during the afternoon 12 to 18 miles per hour. Surface winds 2400CS to 0600CS decreasing to near 4 to 6 miles per hour increasing thereafter 8 to 15 miles per hour.

Winds aloft—below 8000 feet south to southeast 15 to 25 miles per hour—above 8000 feet west to northwest 10 to 20 miles per hour.

c. Route forecasts.—0700CS to 1300CS 7/1/38.

Randolph to Dallas to Shreveport. Cold front lying along Texarkana Gainesville line at 0700CS moving to Shreveport Dallas line by 1200CS. Broken clouds Randolph to Austin becoming scattered

by 0830CS—Scattered the remainder of the period. Scattered clouds Waco-Navasota during entire period—broken to overcast Dallas-Shreveport with thunderstorms developing by 1100CS.

Ceilings 1200 feet Randolph to Austin lifting to 1800 feet by 0830CS and unlimited thereafter. Ceiling unlimited Waco-Navasota during entire period. Ceiling Dallas-Shreveport 800 to 1200 feet along frontal zone and less than 800 feet in scattered thunderstorms, improving to 1500 after passage of front.

Visibility 12 to 15 miles, decreasing 3 to 5 miles in rain along frontal zone.

Surface winds south to southeast 8 to 12 miles per hour shifting at Dallas to northwest 12 to 18 miles per hour after 1200CS.

Winds aloft below 8000, south to southeast 15 to 25 miles per hour above 10,000 feet west to northwest 10 to 20 miles per hour.

Best flying level, 6000 feet, net tail wind 15 miles per hour.

d. Trip forecast.—For BT–9 from Randolph to Oklahoma City. Time of departure 1000CS 10/16/38.

(1) Randolph to Waco—high scattered clouds becoming broken in vicinity of Austin.

Ceilings unlimited to 8000 feet in broken clouds.

Visibilities—unlimited.

Winds aloft—south to southeast 18 to 24 miles per hour. Best flying level, 4000 feet, net tail wind 15 miles per hour.

(2) Waco to Hensley—high broken becoming high overcast. Light showers south of Hensley.

Unlimited ceilings to 8000 feet with ceiling 4000 feet in showers.

Visibility 15 miles becoming 5 miles in precipitation.

Winds aloft—southeast 15 to 24 miles per hour. Best flying level, 6000 feet, net tail wind 20 miles per hour.

(3) Hensley Field to Ardmore—high overcast becoming low overcast with lower broken. Cold front will be encountered between Gainsville and Ardmore with violent thunderstorms.

Ceilings 3000 to 8000 in vicinity of front, becoming 1000 to 1500 after passage of front.

Visibility—5 miles decreasing to ¾ mile in frontal zone, increasing to 2 miles after passage of front.

Winds aloft—East below 4000 feet 12 to 15 miles per hour becoming southeast above 5000 feet 20 to 25 miles per hour. Severe turbulence in frontal zone. Best flying level, 8000 feet, net tail wind 10 miles per hour.

(4) Ardmore to Oklahoma City—low overcast becoming lower broken and lower scattered in vicinity of Oklahoma City.

Ceilings—lifting from 1000 feet to unlimited vicinity of Oklahoma City.

Visibility—increasing from 2 miles to unlimited.

Winds aloft—northeast to north up to 5000 feet becoming northeast to east above 5000 feet. Velocities of from 15 to 20 miles per hour.

Best flying level, 8000 feet, net head wind 10 miles per hour.

he
re
ed
co
in
ak
ey
m
an
es
nd
ed
in

ir
er
on
rs
P
us

m
li-
re
rd
nd
th
r-
es

m
ne
ne

TM 1-
4

C
Cit

eas
hou

he
re
ed
co
in
ak
ey
m
an
es
nd
ed
in

air
er
on
ers
cP
us

m
di-
re
rd
nd
th
er-
es

m
he
he

C
Cit
eas
hou

he
re
ed
co
in
ak
ey
m
an
es
nd
ed
in

air
er
on
ers
cP
us

m
di-
re
rd
nd
th
er-
ies

m
he
he

C
Cit
eas
hou

APPENDIX IV

SYNOPTIC WEATHER MAP

(February 1 and 2, 1939)

High pressure along the Atlantic seaboard in conjunction with the deep low center in Minnesota and the frontal trough of low pressure west of the Mississippi Valley is causing a flow of warm modified maritime polar air (mPw and mPw→mTw) from the Gulf of Mexico to reach the Gulf coast as a warm air mass (mPw). Differences in trajectory with varying degrees of modification are causing weak warm fronts to form in the northward flow up the Mississippi Valley and is producing intermittent rain from the overrunning air. Warm air moving inland comes into contact with a surface now colder than the air, hence is a thermodynamically warm air mass. As it moves over the cooler surface, there is the tendency for advective fog and low stratus clouds to form; however, the wind velocities as reported in the coastal States are sufficient to cause turbulence resulting in stratiform clouds.

North of the warm fronts the cold modified continental polar air (cPk), moves over ground previously snow-covered and is further stabilized in the lower layers. This, together with the precipitation intermittently falling through is tending to saturate the lower layers and to reduce ceilings and visibilities. Air overrunning the mP–cP front paralleling the Great Lakes is causing a region of continuous rain and snow in the vicinity of Lake Superior.

The low-pressure center in Minnesota must move northeast from the area of greatest pressure rise to the area of greatest fall, as indicated by the tendencies around the center. The steep pressure gradient around this low center is causing a rapid inflow southward of fresh cold continental polar air (cPk) which is moving over ground warmer than itself, hence is a thermodynamically cold air mass with respect to the surface. It is near saturation, due to the low temperatures and the lift from convective turbulence causes snow flurries in the Dakotas.

Positive tendency differentials across the trailing cold front from Minnesota to Texas indicate a rapid movement of the front to the east. The relatively "flat" tendency field in Texas indicates that the

southern portion of the front, Texarkana to the Rio Grande, will remain stationary for the next 12 hours.

Orographical lift in the cold nearly saturated cPK air in the elevated areas of New Mexico and Arizona is causing snow areas which are reducing ceilings and visibilities in the southern Rocky Mountains.

Warm modified maritime polar air (mPW) that has been warmed by a long trajectory over the central portion of the Pacific Ocean moves northeast over the slowly moving warm front on the Pacific coast and is producing a widespread rain area ahead of the front. This mPW air occupies the warm sector of a deep cyclone (985 mb.) centered about 300 miles south of Kodiak, Alaska. Fresh, cold maritime polar air (mPK) rapidly moves down (of the map) to the west and southwest of the center behind the mPW–mPK cold front (not shown).

The air occupying the region west of the Continental Divide is warmed continental polar air (cPW) that has recently come out of Canada and has had a brief trajectory over the Pacific around previous cyclonic centers in the northwest. The weak front paralleling the Rocky Mountains separates this air from fresh, cold continental polar air (cPK) east of the Divide.

The main feature of the map is the rapidly occluding wave centered at the northwest edge of Lake Superior and the associated cyclonic system. The center will move northeast as shown by the warm sector isobars and the strong isallobaric gradient. The warm fronts have moved to the northeast with overrunning, causing a large snow area in southern Ontario and intermittent rain south of Lake Huron. Warm maritime tropical air (mTW) is moving northward from the Gulf of Mexico and the instability within the air is indicated by showers in central Louisiana and Mississippi. The primary cold front of this system is moving rapidly and has already caused occlusion of the wave to the vicinity of Detroit. Its further eastward movement is indicated by the large positive tendency differentials across the front. This cold front has moved east about 300 miles in 12 hours in the Lakes region but has remained almost stationary in its southern portion and has maintained the waves along it in Texas. This well-defined front separates fresh cold continental polar air (cPK) behind it from warm modified maritime polar air (mPW) and warm tropical air (mTW) ahead of it. It is a typical squall line and flying within this frontal zone would be very hazardous. Along the retarded portion of this cold front, overrunning by mT air has produced a slender precipitation area along and 150 miles behind it from Texas to Kentucky, with thunderstorms along and behind the front. The waves

in Texas will move to the northeast along the main cold front with attendant rain areas, low ceilings and visibilities, particularly in cP air. These waves will retard the eastward movement of this cP–mT front in the Southern States.

Orographical lift in the cold nearly saturated cPk air in the elevated areas of west Texas, New Mexico, and Arizona is causing snow areas which are reducing ceilings and visibilities in the southern Rocky Mountains.

cP air with a relatively thin but unstable layer near the ground is causing snow flurries in the North Central States and South Central Canada.

The eastward movement of the HIGH in the Atlantic has produced a line of frontogenesis along the east coast between modified mP air and modified cP air that is becoming mT air (cP+mP→mT). The overrunning is causing cloudiness and light intermittent rain in Virginia, Maryland, Delaware, New Jersey, and southern New York. Thunderstorms will develop in the mT air over the Southeastern States due to the weak warm front lift and lift due to convergence of the conditionally unstable air.

Extending from the low pressure center in the Pacific 200 miles northwest of Vancouver Island is a warm front type occlusion caused by the overrunning by mPk air of the colder cPk air banked against the mountains of the west coast. The accompanying general rain area now covers the coast from Sitka, Alaska, to northern California and is extending rapidly toward southern California. The large negative tendencies at coastal stations show that the occlusion will soon move onshore. The fresh mPk air behind the cold front of this system is spotted with instability showers indicating a thermodynamically cold air mass, for the warm ocean surface sets off the conditional instability of the colder air.

APPENDIX V

CONSTANTS AND EQUIVALENTS

1. **Standard values.**—Standard air at sea level has a temperature of 59° F. (15° C.) and is at a barometric pressure of 29.92 in. (1,013 mbs.) (760 mm.) of mercury. Its variation with altitude is shown in the pressure-altitude tables.

Bar ______________ 1,000,000 dynes per sq. cm.

2. **Temperature scales.**—The temperatures of melting ice and of boiling water, each at standard atmospheric pressure, are as follows:

Freezing: 32° F., 0° C., 273° A.
Boiling: 212° F., 100° C., 373° A.

Hence, $\frac{C^\circ}{5}=\frac{F^\circ-32}{9}$

or, $C^\circ=\frac{5}{9}(F^\circ-32)$

or, $F^\circ=\frac{9}{5}C^\circ+32$

3. **Linear equivalents:**
   1 meter=39.37 inches=3.280833 feet.
   1 foot=0.3048006 meter.
   1 kilometer=0.62137 mile=1,000 meters.
   1 mile=1.609347 kilometer.
4. **Velocity equivalents:**
   1 meter per second=2.236932 miles per hour=196.85 feet per minute.
   1 mile per hour=0.4470409 meter per second.
5. **Weight equivalents:**
   1 avoirdupois pound=453.5924277 grams.
   1 kilogram=2.204622 avoirdupois pounds.

6. **Densities** (grams per cubic dentimeter):

Mercury at 0° C	13.5951
Air, dry, at standard pressure and 0° C	0.0012928.
Weight of standard dry air	1.2930 kilograms/per cubic meter; 1.29152 ounce per cubic foot.

7. **Pressure equivalents:**

1 mm. mercury, 0° C=1.333224 millibars=0.03937 inch of mercury.

1 inch of mercury, 0° C=33.863953 millibars=25.4 mms. of mercury.

1 millibar=0.02953 inch of mercury=0.75006 mm. of mercury.

APPENDIX VI

GLOSSARY OF TERMS

ABSOLUTE HUMIDITY—the mass of water vapor present in a unit volume of air or the density of the water vapor.

ABSOLUTELY STABLE—a vertical distribution of temperature, such that whether the air be dry or saturated, particles will tend to remain in their original level. The lapse rate must be less than the saturation adiabat at the prevailing temperatures.

ADIABAT—a curve along which a thermodynamic change takes place without the addition or subtraction of heat. In the case of the atmosphere, a "dry adiabat" is generally considered a temperature-height or temperature-pressure curve along which a rising or sinking air particle will fall providing no saturation occurs and providing that no heat is given to or taken from the particle in its path. Similarly a "wet adiabat" (saturation adiabat, condensation adiabat, or pseudo-adiabat) is a temperature height or temperature-pressure curve along which the saturated rising particle will fall.

ADIABATIC CHART—a thermodynamic diagram in which temperature is plotted against pressure (generally on a logarithmic scale or pressure to the 0.288 power) and in which dry adiabats are constructed. The chief use of this chart is the evaluation of aerological soundings.

ADIABATIC PROCESS—a thermodynamic process in which no heat is transferred from the working substance to the exterior or vice versa; a thermally insulated process.

ADIABATIC RATE OF COOLING WITH ASCENT FOR DRY AIR—very nearly constant in the troposphere at 1° C. per 100 meters. (See ADIABAT.)

ADIABATIC RATE OF COOLING WITH ASCENT FOR SATURATED AIR—a rate which varies chiefly with the temperature and hence has no fixed value.

ADVECTION—the process of transfer by horizontal air movements.

AEROLOGY—The portion of meteorology concerning the free atmosphere.

AIR MASS—an extensive body of air which approximates horizontal homogeneity.

ALTIMETER—an instrument used to measure altitude by means of indicating changes of altitude that result in variations in atmospheric pressure.

ANEMOGRAPH—a recording wind velocity and direction instrument.

ANEMOMETER—an instrument for measuring the velocity of the wind.

ANEROID BAROMETER—an instrument showing atmospheric pressure by the movements of the elastic top of an exhausted metallic box.

ANTICYCLONE—a region in which the barometric pressure is higher than the surrounding air. The wind moves clockwise about the center of an anticyclone.

ARCTIC AIR—air that has its source region over the arctic (or antarctic) ice and snow-covered areas.

ARCTIC SMOKE—a thin wispy fog that occurs chiefly when cold air moves over a much warmer surface.

ASCENDANT—a vector giving the direction and amount of the most rapid rate of increase of a given function, as pressure.

ATMOSPHERIC CIRCULATION—the general wind system of the earth. Also called the "general circulation."

BACKING—a shifting of the wind in a counterclockwise direction. The opposite of VEERING.

BAROGRAPH—a self-recording barometer.

BAROMETER—an instrument for indicating atmospheric pressure.

BLIZZARD—strong winds with accompanying cold and snow.

BUMPINESS—a flying sensation usually caused by instability of the air.

BUYS-BALLOTT'S LAW—the law which states that if an observer in the Northern Hemisphere stands with his back to the wind, lower pressure is on his left.

CENTIGRADE—a temperature scale with 100° between the freezing and boiling points of water, the freezing point being at 0° and the boiling point at 100°. One Centigrade degree equals 9/5 of a Fahrenheit degree. To convert from C. to F., multiply by 9/5 and add 32.

CHARACTERISTIC CURVE—the curve joining the significant points of an aerological sounding when plotted on the Rossby diagram.

CLOUDBURST—a sudden downpour of rain usually accompanied by a thunderstorm.

COLD FRONT—the discontinuity in front of a wedge of cold air which is displacing warmer air in its path.

CONDENSATION LEVEL—the level where the process of formation of water or ice from water vapor begins.

CONDITIONAL INSTABILITY—a vertical distribution of temperature such that the layer is stable for dry air but unstable for saturated air. The lapse rate lies between the dry and the saturated adiabat.

CONVECTION—the transport of heat by moving masses of air.

CONVECTIVE CONDENSATION LEVEL—the condensation level in free convections (usually higher than the lifting condensation level).

CONVECTIVE ICE CRYSTAL LEVEL—level at which ice crystals form in air being lifted by a free convection current. (This level is somewhat higher than the usual ice crystal level due to the fact that more heat is necessary for free convection.)

CONVECTIVE INSTABILITY—a vertical distribution of temperature and moisture such that lifting of the entire layer will eventually lead to instability with respect to dry air. In convective instability the equivalent-potential temperature decreases with elevation.

CONVERGENCE—a state of air movement in which the air is moving inward within a given region. The opposite of divergence.

CURL—a vector function representing the degree of vortex motion about a point. Also used in this manual to represent the visible protruding portions of cumuliform clouds.

CYCLONE—a system of winds circulating about a center of relatively low barometric pressure in a counterclockwise direction. It is frequently called a "depression." Usually caused by a wave on a front.

DEFORMATION AXIS—the line of outflow in a deformation field of motion.

DEFORMATION FIELD OF MOTION—a field of moving particles that combine convergence and divergence.

DENSITY—the mass of a substance per a unit of its volume.

DEPEGRAM—a curve representing the behavior of the dew point with pressure changes for a given sounding drawn on the tephigram.

DEPRESSION—synonym for "cyclone."

DEW—moisture condensed from the atmosphere in small drops upon plants and other bodies which radiate heat well.

DEW POINT—the temperature to which the air must be cooled in order to become saturated.

DISCONTINUITY—a zone of comparatively rapid transition of the meteorological elements. These discontinuities are not mathematically abrupt but are rapid transitions compared with the ordinary transitions in one and the same air mass. (Practically synonymous with FRONT.)

DIURNAL HEATING—heating that takes place daily in a certain cycle from day to day.

DIVERGENCE—a state of the atmosphere when air is flowing outward from a given region.

DOLDRUMS—those parts of the ocean near the Equator where calms prevail.

DRIZZLE—precipitation consisting of numerous and very small drops.

DRY AIR—air which is not saturated.

DUST—pulverized earth carried aloft by the wind.

EDDY—a whirl or backward circling current of water or air.

EQUATORIAL AIR—air originating in equatorial regions.

EQUIVALENT-POTENTIAL TEMPERATURE,—the temperature a given air particle would have if it were brought adiabatically to the top of the atmosphere (that is, to zero pressure) so that along its route all the moisture were condensed (and precipitated), the latent heat of condensation being given to the air, and then the remaining dry sample of air compressed adiabatically to a pressure of 1,000 millibars.

EQUIVALENT-POTENTIAL TEMPERATURE DIAGRAM—see ROSSBY DIAGRAM.

EQUIVALENT TEMPERATURE—the temperature a particle of air would have if it were made to rise adiabatically to the top of the atmosphere (that is, to zero pressure) in such a manner that all the heat of condensation of the water vapor were added to the air and the sample of dry air were then brought back adiabatically to its original pressure.

FAHRENHEIT—a temperature scale in which the freezing point of water is 32° and the boiling point is 212°. One degree Fahrenheit equals $\frac{5}{9}$ of a degree Centigrade. To convert from Fahrenheit to Centrigrade, subtract 32 and multiply by $\frac{5}{9}$.

FOEHN WIND—a dry wind blowing down the leeward slopes of mountains that is warmed by adiabatic heating.

FORCED CONVECTION—the process by which heat is transposed from one locality to another by mechanical movement of the mass containing the heat.

FRICTION LAYER—the lower layer of the atmosphere (usually 1,500 to 3,000 feet thick) in which friction with the earth's surface affects the movement of air. (Synonymous with TURBULENT LAYER.)

FRONT—the discontinuity between two juxtaposed currents of air possessing different densities. Most frequently, fronts represent the boundary between different air masses.

FRONTOGENESIS—the creation of fronts generally brought about through the horizontal convergence of air currents possessing widely different properties.

FRONTOLYSIS—the destruction of fronts generally brought about by horizontal divergence at the discontinuity zone.

FROST—crystals of ice deposited in the same manner as dew.

GALE—a wind of force 8 on the Beaufort Scale.

GLAZE—a deposit of clear, amorphous ice. (Synonymous with CLEAR ICE.)

GRADIENT—a vector giving the direction and amount of the most rapid rate of decrease of a function, as temperature or pressure. The pressure gradient is the change of barometric pressure per unit of distance in the direction of the most rapid rate of decrease of pressure. The vertical temperature gradient is called the "lapse rate."

GRADIENT WIND—the wind that blows along curved isobars with a velocity corresponding to the spacing of the isobars. The wind at 2,000 feet above the surface is often referred to as the gradient wind.

GUST—a rushing or driving of the wind, sudden and of short duration.

HAIL—frozen rain, falling in pellets.

HIGH—a high-pressure area.

HORSE LATITUDES—regions of calm or light variable winds within the subtropical belts of high pressure. So called in Colonial times when vessels carrying horses from New England to the West Indies were sometimes obliged, when detained there, to throw overboard part of their cargo for want of water.

HUMIDITY—the amount of water vapor in the air.

HURRICANE—wind of force 12 on the Beaufort Scale. A tropical cyclone, especially one in the West Indies.

HYGROGRAPH—a recording hygrometer.

HYGROMETER—an instrument for measuring the humidity or gygrometric state of the atmosphere.

INSTABILITY—a vertical distribution of temperature such that the layer of air is unstable, if unsaturated, the lapse rate exceeds the dry adiabatic, and if saturated its lapse rate exceeds the saturation adiabatic.

INSTABILITY SHOWERS—showers caused by steepening of the lapse rate in any way, such as the rapid warming of the lower layers of a cold current as it moves over a relatively warm surface. In most cases there is an appreciable addition of moisture to the lower layers, for example, when a polar continental current moves over a body of warm water.

INVERSION—layer in which the temperature increases with increasing altitude instead of the normal decrease.

ISALLOBAR—a line joining points of equal barometric tendency.

ISALLOBARIC CHART—a chart with isallobars drawn on it.

ISALLOBARIC GRADIENT—a vector representing the direction and magnitude of the most rapid rate of decrease of pressure tendency.

ISOBAR—a line joining points of equal barometric pressure.

ISOLINE—a line joining points of equal values (pressure, temperature, etc.).

ISOTHERM—a line joining points of equal temperature.

LAPSE RATE—the existing rate of change of an element, commonly temperature, with height in a given layer of the atmosphere.

LEVEL OF FREE CONVECTION—the level at which air, clouds, or other meteorological phenomena rise by their own thermal lift.

LIGHTNING—a sudden flash of light caused by the discharge of electricity between two electrified regions of clouds or between a cloud and the earth.

LINE SQUALL—sudden bursts of wind, often accompanied by rain or snow, occurring simultaneously along a line, usually a cold front.

LOOP (OR BENT) BACK OCCLUSION—an occluded front which has bent back in the rear of the cyclone so that it appears in the meteorological field as another front behind the cold front. In most cases these occlusions are of the cold-front type; that is, the air behind is colder than that preceding them.

LOW—a low-pressure area, a cyclone, or a depression, usually caused by a wave on a front.

MECHANICAL INSTABILITY—a lapse rate such that the air density increases with elevation; for this condition the lapse rate must be greater than 3.42° C. per 100 m.

MECHANICAL LIFT—any lift imparted to an air mass by its or another's kinetic energy—not that due to thermal lift.

METEOROGRAPH—an apparatus used in upper air soundings that automatically records temperature, humidity, and pressure.

METEOROLOGY—the science of the atmosphere.

MODIFICATION OF AIR MASS PROPERTIES—the change in values of the meteorological elements within an air mass due to such influences as radiation, turbulence, subsidence, convergence, etc. These modifying influences tend to destroy the original horizontal homogeneity of the air mass.

MONSOON—Winds that consistently blow onshore during the summer and offshore during the winter due to the temperature differential between continental and maritime areas.

MIXING RATIO—the mass of water vapor per unit mass of perfectly dry (absence of water vapor) air. $w = 622e/(p-e)$ grams per kilogram. (See SYMBOLS.)

NEGATIVE AREA—the area on a tephigram enclosed between the path of the rising particle and the surrounding air when the rising particle is at every stage in its ascent colder than the environment.

NEPHOSCOPE—an instrument used in the observation of clouds to determine their direction, velocity, motion, and elevation.

NEUTRAL EQUILIBRIUM—a vertical distribution of temperature such that a particle of air displaced from its level neither assists nor resists the displacement; that is, at every level the density of the displaced particle is equal to that of the surrounding air. In the case of dry air, the corresponding lapse rate is that of the dry adiabat; in the case of saturated air, the saturation adiabat.

OCCLUDED FRONT OR OCCLUSION—the front formed when and where the cold front overtakes the warm front of a cyclone. This front marks the position of an upper trough of warm air, originally from the warm sector, which has been forced aloft by the action of the converging cold and warm fronts. Occlusions may be of the warm front type in which the air in advance of the front is colder than that behind, or of the cold front type, in which the air in advance is the warmer. "Occlusion" is also the term used to denote the process whereby the warm air of the cyclone is forced from the surface to higher levels.

OROGRAPHIC RAIN—rain caused by the lifting of air up the slopes of mountain ranges.

PARTIAL POTENTIAL TEMPERATURE—the temperature a given air particle would have if it were reduced adiabatically from the pressure exerted solely by the dry air to a pressure of 1,000 mb.

$$\Theta d = T \quad 1000/(p-e) \quad 0.288$$ (See SYMBOLS.)

PENETRATIVE CONVECTION—small convective up currents locally penetrating an overlying more stable layer without generally or greatly altering the existing atmospheric stratification.

PILOT BALLOON—a small balloon filled with hydrogen that is released by an observer, who, by the use of a theodolite, is able to determine wind velocity and direction from the movement of the balloon.

POISSON'S EQUATION—the relation between temperature and pressure in dry air which is undergoing adiabatic transformation.

$$T_1/T_2 = (p_1/p_2)^{0.288}$$

POLAR AIR—air originating in the polar regions.

POLAR FRONT—the frontal zone between air masses of polar and those of tropical origin.

POSITIVE AREA—the area on a tephigram enclosed between the path of the rising particle and the surrounding air when the rising particle is at every stage in its ascent warmer than the environment.

POTENTIAL TEMPERATURE—the temperature a given particle of air would have if it were reduced adiabatically to a pressure of 1,000 mb.

$$\Theta = T(1{,}000/p)^{0.288}$$

PRECIPITATION—the deposition of moisture from the atmosphere upon the general surface of the earth.

PSUEDO-ADIABATIC—the process wherein a saturated air particle undergoes adiabatic transformations, the liquid water being assumed to fall out as it is condensed.

RADIO METEOROGRAPH (RADIO-SONDE)—an instrument that automatically records temperature, humidity, and pressure as it is carried aloft by a hydrogen-filled balloon. It records by a system of breaks in radio code that is transmitted automatically. A parachute carries the instrument to earth after the balloon bursts.

RAIN—water droplets that fall from clouds.

RECTILINEAR—pertaining to, or consisting of, a right line or lines.

RELATIVE HUMIDITY—the ratio of the actual vapor pressure and the maximum vapor pressure possible at the same temperature.

$$f = e/e_m \quad \text{(See SYMBOLS.)}$$

REPRESENTATIVE OBSERVATIONS—those which give the true or typical conditions of the air mass; hence they must be relatively uninfluenced by local conditions and taken from outside the transition zones and fronts.

ROSSBY DIAGRAM—a thermodynamic diagram making use of the highly conservative air mass properties; partial potential temperature, equivalent-potential temperature, and mixing ratio.

SANDSTORM—a high wind which carries dust or sand with it.

SCUD—patches of low, rapidly drifting clouds.

SECONDARY LOW—a low pressure area or wave that develops along one of the fronts associated with a primary or larger cyclone.

SECONDARY FRONTS—fronts which develop at some distance from the principal fronts of the cyclone. These fronts are often the result of dynamic effects behind the cold front, or are merely loop back occlusions.

SHOWER—isolated precipitation falling from cumuliform clouds.

SLEET—frozen rain.

SLOPE OF A FRONT—the tangent of the angle formed by the discontinuity surface and a horizontal plane.

SNOW—precipitation in the form of minute ice crystals formed by sublimation of the water vapor in the air and usually falling in irregular masses or flakes.

SOURCE REGION—an extensive area of the earth's surface characterized by sufficiently uniform surface conditions and which is so placed in respect to general circulation that masses of air may remain over them sufficiently long to take on fairly definite properties.

SPECIFIC HUMIDITY—the mass of water vapor in a unit mass of moist air. $q=622\ e/p$ grams per kilogram.

SQUALL—a sudden burst of wind usually accompanied by rain or snow.

SQUALL HEAD—the piled-up cold air at the cold front, sometimes taking the form of an overhanging tongue.

STABILITY—a vertical distribution of temperature such that particles will resist displacement from their level. In the case of dry air the lapse rate for stability will be less than the dry adiabat; in that of saturated air, less than the saturation adiabat.

STORM—a wind of force 11 on the Beaufort Scale. There are also various types of storms such as thunderstorm, snowstorm, rainstorm, duststorm, and sandstorm.

STRATIFICATION—a layering of the atmosphere so that each layer is characterized by a particular temperature distribution and moisture content. Instability tends to wipe out stratification as it brings about mixing.

STRATOSPHERE—a layer of the atmosphere above the troposphere in which the air is stable with an isothermal lapse rate or a slight inversion.

SUBSIDENCE—an extensive sinking process most frequently observed in polar anticyclones. The subsiding air is dynamically warmed and made more stable.

SURFACE OF DISCONTINUITY—the sloping boundary zone between air masses of different properties. (See DISCONTINUITY.)

SYMBOLS—used throughout the series and in the formulas given herein:

e	vapor pressure.
f	relative humidity.
G	pressure gradient.

P	total pressure.
p	pressure; pressure of the dry air; pressure at a center, front, trough, or wedge line.
p', p''	pressure at a unit length ahead of and in rear respectively of a center, trough, wedge, or front.
q	specific humidity.
T	temperature; barometric tendency.
t	error in time.
w	mixing ratio.
Δ_p	pressure difference between two isobars.
Δ_s	distance between two isobars.
Θ	potential temperature.
Θ_E	equivalent-potential temperature.
Θ_d	partial-potential temperature.
ϕ	latitude.
ρ	density of the air.
V	geostrophic or gradient wind.
Z	altitude.

SYNOPTIC CHART—a weather map showing the weather conditions over a large area at a given time.

TEPHIGRAM—a thermodynamic diagram for estimating the quantity of available convective energy in the overlying air column; also applied to the graph of an individual sounding plotted with coordinates temperature and estropy.

THERMAL—pertaining to, determined by, or measured by heat.

THERMOMETER—an instrument for measuring temperature.

THERMOGRAPH—a recording thermometer.

THUNDER—the sound that accompanies lightning, due to the disturbance of the air by the electrical discharge.

TORNADO—a very violent storm of small extent, usually occurring along or ahead of a cold front, accompanied by rain or hail and usually thunderstorms, and having cyclonic rotation with a funnel-shaped cloud.

TRADE WIND—a steady wind that blows from the subtropical high pressure belts to the region of lower pressure near the Equator, from the northeast in the Northern Hemisphere, and from the southeast in the Southern Hemisphere.

TRANSITION ZONE—the zone at a discontinuity wherein the properties are neither characteristic of one air mass nor the other, but lie somewhere between the two. It is now customary to assume that all the air in the transitional zone belongs to the colder air mass, the air in warm sectors being considered more nearly homogeneous.

TRANSLATION—motion in which all points of the moving body have at any instant the same velocity and direction of motion.

TROPICAL AIR—air originating in the low latitudes, chiefly in the regions of the subtropical anticyclone.

TROPICAL CYCLONE—a cyclone of great intensity, usually round, originating in the Tropics, and usually having a diameter of about 500 miles. (See HURRICANE.)

TROPOPAUSE—the upper limit of the troposphere.

TROPOSPHERE—the lower layer of the atmosphere in which there is normally a lapse rate of 6° C./km. It is the convective portion of the atmosphere.

TROUGH—an elongated area of relatively low pressure usually extending from a cyclonic center and continuing a front along the line of minimum pressure.

UNSTABLE—a vertical distribution of temperature such that particles of air, because of their lesser or greater density than the surrounding air, will rise or sink of their own accord once given an initial impetus up or down. In dry air, the unstable lapse rate is greater than the dry adiabat; in saturated air, greater than the saturation adiabat.

V-SHAPED DEPRESSION—a trough containing a well-defined front, usually a cold front, with V-shaped isobars.

VAPOR PRESSURE—the partial pressure of the air exerted solely by the water vapor molecules.

VEERING—a more or less gradual clockwise change of wind direction. The opposite of BACKING.

VIRGA—trailer of rain or snow from clouds.

VISIBILITY—the maximum distance at which ordinary objects may be identified.

VORTEX—a portion of fluid whose particles have rotary motion.

WARM FRONT—the discontinuity at the front of a warmer air mass which is displacing a retreating colder air mass.

WARM SECTOR—the air enclosed between the cold and warm fronts of a cyclone.

WATERSPOUT—a tornado cloud at sea.

WAVE DISTURBANCE—a deformation produced along a front. These waves travel along the discontinuity surface producing new disturbances.

WEDGE—an elongated area of relatively high pressure extending from an anticyclone.

WIND—air in motion.

Appendix VII

BIBLIOGRAPHY OF METEOROLOGY

G. F. TAYLOR, "Aeronautical Meteorology", Pitman Publ. Co., N. Y.—Chi., 1938, 429 pp. $4.50. (Good general text.)

P. H. V. WEEMS, "Air Navigation", "Outline of Meteorology" by Dr. Sverre Petterssen, pp. 426–514, McGraw-Hill Book Co., Inc., 1938.

H. R. BYERS, "Synoptic and Aeronautical Meteorology", 279 pp., McGraw-Hill Book Co., Inc., 1937.

A. JORDANOFF, "Through the Overcast", Funk and Wagnall's Co., 1938, 356 pp.

J. NAMIAS, "An Introduction to the Study of Air Mass Analysis", "Bulletin", pp. 1–22, Oct., 1938.

H. C. WILLETT, "American Air Mass Properties", Papers in Physical Oceanography and Meteorology, Mass. Inst. of Tech. and Woods Hole Oceanographic Inst., Vol. II, No. 2, 116 pp., 1933. (Out of print.) Abstr., "Journ. Aeronaut. Sci.", Apr., 1934.

J. BJERKNES, "On the Structure of Moving Cyclones", Geofys. Publ., Vol. I, No. 2, 8 pp., 1918, Kr. 1.50. Repr., Mo. Wea. Rev., Feb., 1919, pp. 90–99.

J. BJERKNES & H. SOLBERG, "Meteorological Conditions for the Formation of Rain", Geofys. Publ., Vol. II, No. 3, 60 pp., 1921, Kr. 6.00.

J. BJERKNES & H. SOLBERG, "Life Cycle of Cyclones and the Polar Front Theory of Atmospheric Circulation", Geofys. Publ., Vol. III, No. 1, 18 pp., 1922, Kr. 2.00. Rev'd. in "Mo. Wea. Rev.", Sept., 1922, pp. 468–474.

C. G. ROSSBY, "Thermodynamics Applied to Air Mass Analysis", Mass. Inst. of Tech., Meteorological Papers, Vol. I, No. 3, 41 pp., 1932, $1.00.

J. BJERKNES, "Practical Examples of Polar Front Analysis over the British Isles in 1915–1926", Geophysical Memoirs, No. 50, Meteorological Office, London. (Out of print.) Prelim. abstr., Met. Mag., Mar., 1926, pp. 32–33.

J. NAMIAS, "Structure of a Wedge of Continental Polar Air Determined from Aerological Observations", Mass. Inst. of Tech., Meteorological Course, Professional Notes, No. 6, 39 pp., 1934, $0.75.

H. C. WILLETT, "Dynamic Meteorology", National Research Council, Bulletin 79, pp. 133–233, 1931, $3.00.

C. G. ROSSBY & R. H. WEIGHTMAN, "Application of the Polar Front Theory to a Series of American Weather Maps", Monthly Weather Review, Vol. 54, pp. 485–496, 1936.

H. R. BYERS, "Characteristic Weather Phenomena of California", Mass. Inst. of Tech. Meteorological Papers, Vol. I, No. 2, 54 pp., 1931, $1.00.

H. C. WILLETT, "Fog and Haze", . . ., Monthly Weather Review, Vol. 56, Nov., 1928, pp. 435–468.

H. C. WILLETT, "Discussion and Illustration of Problems Suggested by the Analysis of Atmospheric Cross Sections", Papers in Phys. Oceanogr. and Met., Mass. Inst. Tech., Vol. 4, No. 2, 1935, 41 pp. $1.00.

J. BJERKNES, "Investigations of Selected European Cyclones by Means of Serial Ascents", Geofysiske Publikasjoner, Vol. 11, No. 4, 1935, 18 pp. Kr. 2.

E. GOLD, "Fronts and Occlusions", Quart. Journ. Roy. Met. Soc., Vol. 61, Apr., 1935, pp. 107–158. A history and summary of the subject.

D. BRUNT, "Physical and Dynamical Meteorology", pp. 16–17, 190–195, 290–372, N. Y., 1935. $7.00.

G. EMMONS, "Atmospheric Structure over the Southern United States", Dec. 30–31, 1927. "Determined with the Aid of Sounding Balloon Observations", Mass. Inst. Tech., Met. Course, Professional Notes, No. 9, 1935. 58 pp. $1.00. (Summ. in Bull. Am. Met. Soc., Aug.–Sept., 1936, pp. 268–271.)

C. K. M. DOUGLAS, "Further Researches into the European Upper Air Data", Quart. Journ. Roy. Met. Soc., Vol. 50, 1924, pp. 339–363.

———, "The Physical Process of Cloud Formation", ibid., Vol. 60, 1934, pp. 333–334.

———, "The Problem of Rainfall", ibid., Vol. 60, 1934, pp. 143–152.

H. R. BYERS, "The Air Masses of the North Pacific", Scripps Inst. of Oceanography Bulletin, Technical Series, Vol. 3, 1934, No. 14, pp. 311–354. $1.00.

S. PETTERSSEN, "Kinematical and Dynamical Properties of the Field of Pressure With Applications to Forecasting", Geofysiske Publikasjoner, Vol. 10, No. 2, Kr. 9.00.

I. P. KRICK, "Foehn Winds of Southern California", Gerlands Beitrage z. Geophysik, Vol. 39, 1933, pp. 399–407.

H. C. WILLETT, "Synoptic Studies in Fog", Mass. Inst. Tech. Met. Papers, Vol. 1, No. 1, 1932, 50 cents.

J. NAMIAS, "Subsidence Within the Atmosphere", Harvard Meteorological Studies, No. 2, 1934, Harvard Univ. Press, Cambridge, Mass., 85 cents. Abstr. BULLETIN, Jan., 1936, pp. 20–21; prelim. art., Trans. Am. Geophys. Un., 1934, pp. 105–114.

E. W. HEWSON, "The Application of Wet-bulb Potential Temperature to Air Mass Analysis", I–IV, Quart. Journ. Roy. Met. Soc., July, 1936, pp. 387–420; Jan. 1937, pp. 7–30; July, 1937, pp. 323–338, 431; July, 1938, pp. 407–422.

H. WEXLER, "Analysis of a Warm-Front Type Occlusion", Monthly Weather Review, Vol. 63, July, 1935, pp. 213–221.

F. W. REICHELDERFER, "Report on Norwegian Methods of Weather Analysis", Bur. of Aeronautics, Navy Dept., 1932 (corrections, 1935) mimeo., 45 pp.

H. R. BYERS, "The Use of Free-Air Soundings in General Forecasting", Monthly Weather Review, Oct., 1934, pp. 376–378.

J. BJERKNES & C. L. GODSKE, "On the Theory of Cyclone Formation at Extra-Tropical Fronts", Astrophysica Norvegia, Vol. 1, No. 6, 1936, pp. 200–235.

S. PETTERSSEN, "On the Causes and the Forecasting of the California Fog", Journ. Aeronaut. Sci., Vol. 3, No. 9, July, 1936, pp. 305–309. Reprinted, BULLETIN, Feb., 1938, pp. 49–55.

H. WEXLER, "Cooling in the Lower Atmosphere and the Structure of Polar Continental Air", Mo. Wea. Review, Vol. 64, No. 4, Apr., 1936, pp. 122–135.

REV. C. E. DEPPERMANN, S. J., "Outlines of Philippine Frontology", Wea. Bur., Manila, 1936, 27 pp.

T. BERGERON, "The Physics of Fronts" (English abstract of Pt.II of "Uber die dreidimensional Verkn. Wetteranalyse," 1928), planographed, the author, 1936 (full paper to appear later in Geophys. Publ.). Reprinted in BULLETIN, Sept., 1937, pp. 265–275.

E. J. MINSER, "Icing of Aircraft", Air Commerce Bulletin, Dec. 15, 1934, and reprinted in BULLETIN, May, 1935, pp. 129–133.

T. BERGERON, "On the Physics of Cloud and Precipitation", Proces Verbaux de la Seance de l'u. G. G. I. a lisbonne 1933, Paris, 1935.

C.-G. ROSSBY & COLLABORATORS, "Aerological Evidence of Large Scale Mixing in the Atmosphere", Transactions of the American Geophysical Union, 18th Annual Meeting, 1937, Pt. I, pp. 130–136.

C.-G. ROSSBY & COLLABORATORS, "Isentropic Analysis", Bulletin of the American Meteorological Society, June–July, 1937, vol. 18, pp. 201–209.

H. WEXLER, "Formation of Polar Anticyclones", Mon. Wea. Rev., June, 1937, pp. 229–236.

H. R. BYERS, "On the Thermodynamic Interpretation of Isentropic Charts", Mon. Wea. Rev., Mar. 1938, pp. 68–70.

W. R. STEVENS, "Relation of Pressure Changes to Cyclones and Fronts", Mon. Wea. Rev., Mar., 1938, pp. 68–70.

B. C. HAYNES, "Upper-Wind Forecasting", Mon. Wea. Rev., Jan., 1938, pp. 4–5.

H. R. BYERS, "Synoptic and Aeronautical Meteorology", McGraw-Hill, N. Y., 1937, 279 pp., $3.75. Review in BULLETIN, June, 1938. (Good general text.)

E. J. MINSER & G. HATHAWAY, "Synoptic Analysis of Some Excessive Rainfalls in the Mississippi Basin due to Squeezing of Tropical Air Between Anticyclones", BULLETIN, Jan., 1938, pp. 34–42.

J. NAMIAS, "Thunderstorm Forecasting with the Aid of Isentropic Charts", BULLETIN, Jan., 1938, pp. 1–14.

F. B. WOOD, "The Formation and Dissipation of Stratus Clouds Beneath Turbulence Inversions", Prof. Notes, Met. Course, Mass. Inst. Tech., No. 10, Dec., 1937, 27 pp., $0.75. Summary in BULLETIN, March, 1938, pp. 97–103.

E. J. MINSER, "Studies of Synoptic Free-Air Conditions for Icing of Aircraft", BULLETIN, Mar., 1938, pp. 111–122.

B. HOLZMAN, "Synoptic Determination and Forecasting Significance of Cold Fronts Aloft", Mon. Wea. Rev., Dec., 1936, pp. 400–413. Summary in BULLETIN, Jan., 1937, pp. 1–5.

S. LICHTBLAU, "Upper-Air Cold Fronts in North America", Mon. Wea. Rev., Dec., 1937, pp. 43–46.

J. J. GEORGE & W. M. BRADLEY, "A Semi-quantitative Method of Forecasting Summer Stratus in N. American Tropical Maritime Air", Mon. Wea. Rev., Feb., 1937, pp. 43–46.

J. A. RILEY, "Aircraft Icing Zones on the Oakland-Cheyenne Airway", Mon. Wea. Rev., Mar., 1937, pp. 104–108.

J. BJERKNES & E. PALMEN, "Investigation of Selected European Cyclones by means of Serial Ascents, Case 4": Feb. 15–17, 1935, Geofys. Publ., Vol. XII, No. 2, 1937, 62 pp., Kr. 8:00.

———, "International Atlas of Clouds and of States of the Sky", Vol. No. 1 (General Atlas), Office National Meteorologique, Paris.

I. P. KRICK, "Foehn Wind Cyclo-Genesis", Calif. Inst. of Tech. (Reprinted from "Gerlands Beitrage Zur Geophysik", Vol. 42, pp. 56–59, 1934, Akademische Verlagsgesellschaft m. b. N. in Leipzig.)

I. P. KRICK, "Forecasting the Dissipation of Fog and Stratus Clouds", Journ. of the Aeronaut. Sci., July, 1937, pp. 366–371.

Office of the Chief of the Air Corps, U. S. A., "Training Guides Meteorology". 2 Vols. Rev. Ed. 1938, 267 pp. plus maps.

B. HOLZMAN, "Sources of Moisture for Precipitation in the U. S.", U. S. Dept of Agric. Techn. Bull. No. 589, Oct., 1937.

B. HOLZMAN, "Use of Aerological Soundings in Determining Sources of Moisture for Precipitation", Trans. Amer. Geophys. Un., 1937, Pt. II, pp. 488–490.

B. HOLZMAN, "Detailed Characteristics of Surface Fronts", BULLETIN, Apr.–May, 1937, pp. 155–159.

I. I. SCHELL, "Chromov's Rules for Forecasting Synoptic Situations", BULLETIN, 1935, pp. 21–22, 71–73, 108–110.

H. ARAKAWA, "The Air Masses of Japan", BULLETIN, Dec., 1937, pp. 407–410.

H. C. WILLETT, "The Importance of Observations from the Upper Atmosphere in Long-Range Weather Forecasting", BULLETIN, Sept., 1937, pp. 284–287.

P. F. CLAPP, "The Causes and Forecasting of Fogs at Cheyenne, Wyo.", BULLETIN, Feb., 1938, pp. 66–73.

R. G. STONE, "Fog in the United States and Adjacent Regions", Geog. Rev., Jan., 1936, pp. 110–136.

H. G. HOUGHTON, "Problems Connected with the Condensation and Precipitation Processes in the Atmosphere", BULLETIN, April, 1938, pp. 152–159.

E. SCOFIELD, "On the Origin of Tropical Cyclones", BULLETIN, June, 1938, pp. 225 ff.

E. M. VERNON, "The Diurnal Variation in Ceiling Height Beneath Stratus Clouds", Mon. Wea. Rev., Jan., 1936.

U. S. WEATHER BUREAU, "Distribution of Weather Information by Radio", Radio Circ. No. 1, Rev. Jan., 1938, 54 pp. mimeo.

U. S. WEATHER BUREAU, "Instructions for Airways Meteorological Service", Circ. N., Aerolog. Div., 3d Ed., 1935.

U. S. WEATHER BUREAU, "The Preparation of Manuscript Maps", Circular, 6 pp., Apr., 1937.

C. E. DEPPERMANN, "Are There Warm Sectors in Philippine Typhoons?", Wea. Bur., Manila, 1937, 19 pp.

C. E. DEPPERMANN, "The Upper Air at Manila", Publ. Manila Obsy., Vol. 2, No. 5, 1934.

C. E. DEPPERMANN, "Typhoons Originating in the China Sea", Phil. Wea. Bur., 1938.

W. N. SHAW, "Manual of Meteorology", Vol. III, 1930, Vol. IV, 1931.

A. H. R. GOLDIE, "Characteristics of Rainfall Distribution in Homogeneous Air Currents and at Surfaces of Discontinuity-----", Geophysical Memoirs No. 53, Met. Off., London, 1931, 19 pp. 1s/6d.

S. PETTERSSEN, "Practical Rules for Prognosticating the Movement and the Development of Pressure Centers", Proces Verbaux d. s. de L'Assoc. de Met., Pt. 2, Un. Geod et Geophys. Int., 5th Assemb., 1933, Lisbon. Paris, 1935, pp. 35–70.

S. PETTERSSEN, "Contribution to the Theory of Frontogenesis", Geofys. Publ., Vol. XI, No. 6, 1936. Kr. 3:00.

C. K. M. DOUGLAS, "Rainfall from Above 6,000 Feet, in Relation to Upper Winds and Fronts", Quart. Journ. Roy. Met. Soc., April, 1936, pp. 207–218.

C. K. M. DOUGLAS, "Fronts and Depressions", Meteorological Mag., Mar., 1936, pp. 34–39.

D. BLAKE, "Mexican West Coast Cyclones", Mo. Wea. Rev., Dec., 1935, pp. 344–347.

A. K. SHOWALTER, "Frontal Movements Contrary to the Indicated Gradient Flow Produced by Minor Waves", Mo. Wea. Rev., June, 1938, pp. 165–174.

M. E. CRAWFORD, "A Statistical Study of Summer Stratus over South Texas", Mo. Wea. Rev., May, 1938, pp. 131–133.

A. A. LOTHMAN, "Fog Forecasting for Fire Control in Southern California", Mo. Wea. Rev., May, 1938, pp. 135–138.

C. G. ROSSBY, "On the Role of Isentropic Mixing in the General Circulation of the Atmosphere", to appear in "Trans. of the 5th Int. Congress of Applied Mechanics," Cambridge, Mass., 1938.

C. G. ROSSBY, J. NAMIAS & R. G. SIMMERS, "Fluid Mechanics Applied to the Study of Atmospheric Circulations, Pt. I, a Study of Flow Patterns with the Aid of Isentropic Analysis", Mass. Inst. Tech. and Woods Hole Oceanogr. Inst., Papers in Physical Oceanogr. and Met., Vol. VII, 1938.

A few foreign books and papers are listed below:

S. P. CHROMOW, "Einfuhrung in die Wetteranalyse", Moscow, 1934, the Central Office of the Hydro-meteorological Service. About 450 pages, all in Russian, of condensed compilation of practically everything of importance which has been written in synoptic meteorology, together with a rather exhaustive bibliography of such. (2d Ed., Rev. and Enl., 510 pp., Moscow, 1937.)

T. BERGERON, "Uber die dreidimensional verknupfende Wetteranalyse, Teil I", Geofysiske Publikasjoner, Vol. 5, No. 6, Oslo, 1928, Kr. 14.00. Contains a complete bibliography of papers in synoptic meteorology written previous to 1928.

T. BERGERON & G. SWOBODA, "Wellen und Wirbel an einer quasistationaren Grenzflache uber Europa", Veroffentlichungen des Geophysikalischen Instituts der Universitat Leipzig, Bd. 3, Hf. 2, Leipzig, 1924, (Out of print.) Rev'd, in Mo. Wea. Rev., 1936, pp. 458–459.

G. SCHINZE, "Die Praktische Wetteranalyse", Aus dem Archiv der Deutschen Seewarte, Bd. 52, Nr. 1, 72 pp., Hamburg, 1932, RM. 3.00.

H. SOLBERG, "Schingungen und Wellenbewegungen in einer Atmosphare mit nach oben abnehmender Temperatur", Astrophysica Norvegica, Vol., 2 no. 2, pp. 124–172, 1936. Kr. 3.25.

H. EXTERNBRINK, "Ein Beitrag zum Wettergeschehen im Golf von Mexiko, im Karibischen Meer und auf den Westindischen Inseln", Met. Zeit., Oct., 1937, pp. 354–359; Nov., 1937, pp. 313–317.

R. MUGGE, "Wolken in Bewegung", Met. Zeit., March, 1937, pp. 81–90.

J. BJERKNES, "Theorie der aussentropischen Zyklonenbildung", Met. Zeit., Dec., 1937, pp. 462–466.

V. BJERKNES, J. BJERKNES, H. SOLBERG, & T. BERGERON, "Hydrodynamique Physique", 3 vols., Paris, 1934, Presses Univ. de France. Vol. III espec.

A. REFSDAL, "Das Aerogramm, Ein neues Diagrammpapier fur Aerologische Berechnungen", Met. Zeits., Vol. 52, No. 1, Jan., 1935, pp. 1–5. "Aerologisches Diagrammpapier", Geof. Publ. Vol. XI, No. 13, 1937. (Translated by OCAC, 1939.)

S. PETTERSSEN," Kinematical and Dynamical Properties of the Field of Pressure with Application to Weather Forecasting", Oslo 1933, Grondahl & Sons Boktrykkeri, pris Kr. 9.00. (An excellent paper.)

NOTE.—The word "BULLETIN" in this bibliography refers to the "Bulletin American Meteorological Society."

[A. G. 062.11 (10-6-39).]

BY ORDER OF THE SECRETARY OF WAR:

G. C. MARSHALL,
Chief of Staff.

OFFICIAL:
E. S. ADAMS,
Major General,
The Adjutant General.

U. S. GOVERNMENT PRINTING OFFICE: 1940

For sale by the Superintendent of Documents, Washington, D. C. - - - - - - - - - - Price 40 cents